JSC-09106

TRACKING AND COMMUNICATIONS DEVELOPMENT DIVISION

INTERNAL NOTE

FREQUENCY STANDARD STABILITY FOR DOPPLER MEASUREMENTS ON-BOARD THE SHUTTLE

(NASA-TM-X-72030) FREQUENCY STANDARD STABILITY FOR DOPPLER MEASUREMENTS ON-BOARD THE SHUTTLE (NASA) 110 p HC $5.25 CSCL 22B

N75-10156

Unclas

G3/18 53607

DISTRIBUTION AND REFERENCING

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

July 1974

LEC-3964
SHUTTLE

TRACKING AND COMMUNICATIONS DEVELOPMENT DIVISION INTERNAL NOTE

FREQUENCY STANDARD STABILITY FOR DOPPLER MEASUREMENTS ON-BOARD THE SHUTTLE

APPROVED BY

W. E. Zrubek
Chief, ~~Tracking~~ Techniques Branch

Ralph S. Sawyer
Chief, Tracking and Communications Development Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS

July 1974

LEC-3964

FREQUENCY STANDARD STABILITY FOR DOPPLER MEASUREMENTS ON-BOARD THE SHUTTLE

Job Order 16-609

PREPARED BY

P. L. Harton, Staff Engineer

APPROVED BY

A. C. Lindberg, Supervisor
Tracking and Laser Systems Section

L. R. Watkins, Mananger
Tracking and Communications Systems Department

Prepared By

Lockheed Electronics Company, Inc.

For

Tracking and Communications Development Division

Under Contract NAS 9-12200

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

July 1974

LEC-3964

ACKNOWLEDGMENTS

This document was prepared by Lockheed Electronics Company, Inc., Aerospace Systems Division, Houston, Texas, Space Center, under Contract NAS 9-12200, Job Order 16-609. It was written by P. L. Harton, Staff Engineer, and approved by A. C. Lindberg, Supervisor of Tracking and Laser Systems Section and by L. R. Watkins, Manager of Tracking and Communications Systems Department, Lockheed Electronics Company, Inc.

CONTENTS

CONTENTS (Concluded)

TABLES

FIGURES

FIGURES (Concluded)

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AGC	Automatic Gain Control
dB	Decibel
hr	A one hour unit of time
Hz	Hertz, one cycle per second
Loran-C	The "C" version of a long range navigation system
MHz	Megahertz, one million cycles per second
NAA	Navy radio station at Cutler, Maine
NAFS	Newark Air Force Station, an Air Force metrology center.
NBS	National Bureau of Standards
NLK	Navy radio station at Jim Creek, Washington
NSS	Navy radio station at Annapolis, Maryland
Q	A quality factor for resonant circuit, a ratio of energy stored to energy dissipated.
rms	Root-mean-square
s	A 1 second unit of time.
USNO	United States Naval Observatory
UTC	Universal coordinated time
VLF	Very low frequency, any frequency within the range from 3 to 30 kilohertz.
WWV WWVB WWVH WWVL	Call letters for the National Bureau of Standards frequency and time dissemination radio stations.

$a(t)$ A time-varying component of the amplitude of a frequency standard signal.

d_1 A long-term frequency deviation, with respect to an initial value.

d_2 An instantaneous deviation of frequency from a long-term trend of frequency as a function of time.

d_3 An instantaneous deviation of frequency, from an initial value.

d_4 An instantaneous frequency deviation, from a long-term average value.

d_5 The instantaneous frequency difference between a long-term average frequency and a time-trend line.

e A constant, equal to 2.718.....

$e_s(t)$ The symbol for a frequency standard signal, expressed as a function of time.

f The nominal frequency of a signal source. A subscript is used when a particular source is to be designated.

f_{av} The average frequency for a particular period of observation.

f_d The difference between the frequencies of two oscillators.

f_m The mean frequency of a signal source.

f_n The nth frequency, where $n = 1, 2, 3, \ldots$

f_o The initial frequency of a signal source, at the beginning of an observation period.

f_t The frequency of a signal source at a particular instant in time or averaged over a known interval of time.

$f(t)$ The frequency of a signal source, expressed as a function of time.

A — The mean amplitude of a frequency standard signal.

A — A designated channel of the vector voltmeter.

B — A designated channel of the vector voltmeter.

F — Fractional frequency deviation; also used to represent the farenheidt temperature scale.

N — A number of measurements in a sequence to be used for computing fractional frequency fluctuation, or the variance in observed frequency; also used to represent a number of cycle counts.

$R_\varphi(\tau)$ — The autocorrelation function for random phase noise of a frequency standard signal, defined for a finite delay of τ seconds.

$S_y(f)$ — The power spectral density of the fractional frequency fluctuation.

$S_\varphi(f)$ — The spectral density of phase angle fluctuations, a frequency - domain expression.

$S_{\dot\varphi}(f)$ — A time rate of change in the phase spectral density; hence, a frequency spectral density.

T — An observation period, including τ seconds of measurement and an elapsed time between measurement intervals; also used as an averaging period.

T_p — The period of a particular wave.

T_p — The measured period of the difference between two frequency standard signals.

g	The force of gravity under standardized conditions, used here as a unit of force during shock and vibration.
j	The imaginary operator, which rotates a given phasor by 90° in a counter-clockwise direction.
m	An arbitrary number of sample differences.
n_f	A noise-like fluctuation of frequency, with time.
r	The correlation coefficient, a statistical measure of the degree to which two variables are related.
s	The standard deviation of a set of stability measurements.
${s_r}^2$	A residual variance, after regression or some similar data processing procedure.
t	The time variable.
t_d	A time variable symbol for which the units are days.
t_k, $t_{k+\tau}$	The kth instant in time and a successive instant, τ seconds later, each period being τ seconds in duration.
t_n	A particular time, denoted by the subscript to be a number (n) of time intervals after an initial instant in time.
u	The mean of a population.
$(x_1, x_2, x_3, \ldots, x_n)$	A time series of stability measurements; also used without the subscript to represent the independent variable in the normal density function.
$\bar{x}$	The mean of a set of stability measurements.
$y(t)$	Instantaneous fractional frequency deviation.

$\bar{y}_k$, $\bar{y}_{k+1}$ Mean values of fractional frequency fluctuation for the kth and successive observation intervals.

$\bar{y}_n$ The nth mean in a sequence of fractional frequency deviation measurements.

z The standard deviate, a normalized variable for the normal density function.

FREQUENCY STANDARD STABILITY FOR DOPPLER

MEASUREMENTS ON-BOARD THE SHUTTLE

1.0 SUMMARY

Attention is focused on crystal and atomic frequency standards, as elements of a system configuration for making one-Way Doppler measurements on-board the Shuttle. Emphasis is placed on crystal standard performance in the Shuttle environment because crystal standard specifications have been used for the Shuttle frequency reference.

Sensitivities in the order of 1 part in 10^9 are noted for the effects of acceleration and vibration on crystal standard frequencies. Typical aging rates from 1 part in 10^9 to values lower than 1 part in 10^{11} are considered to be feasible as a result of literature studies. Reports on the performance of spaceborne crystal standards show the effects on aging rates to vary. In one case, the rate was observed to be relatively unaffected. In another case, the rate was seen to vary from a positive value, through zero to a negative value, and finally to drift slowly back toward zero.

Effects of the space environment on aging rate appear to include an effect of radiation. One report notes a fractional frequency shift of about 0.5×10^{-9} during a period of about one day. It appears that launching forces and radiation may combine to produce effects on the frequency stability of a crystal standard which can be bounded in magnitude, but not precisely predicted at this time.

Frequency stability terminology is reviewed in relation to the Shuttle application. Examples are provided from calibration measurements that are now being made, in preparation for tests on one-way Doppler equipment. These examples illustrate an approach for the development of an error model that would include stability effects of the ground station and Shuttle frequency standards.

2.0 INTRODUCTION

Two frequency standards, or reference frequency sources, are to be used in the system configuration for making one way Doppler measurements on-board the Shuttle. The system error budget will include contributions from each of these sources. The reference frequency source that is to be used on-board the Shuttle will be subjected to rather severe environmental conditions.

Consideration has already been given to the selection of a reference source for the Shuttle baseline and a specification has been prepared[1]. The decision was made to use a crystal oscillator, rather than an atomic standard for this purpose. Atomic standards will be used, however, at the ground station installations. This report has been prepared to describe the short and long term stability characteristics of crystal and atomic standards. Emphasis is placed on crystal oscillators because of the selection which has been made for the Shuttle baseline and the complexities which are introduced by the Shuttle environment.

Attention is given, first, to the definitions of stability and the application of these definitions to the Shuttle system and its mission. Data from time domain measurements are used to illustrate the definitions. These data are of interest because they are from initial calibration tests of a configuration that is to be used in tests on one-way Doppler (OWD) equipment. Statistical treatments of these data illustrate methods to be used in error model development and in the implementation of OWD test plans[2,3].

The results of a literature survey to determine environmental effects on frequency reference sources is presented next. Finally, methods of standard frequency dissemination over radio frequency carriers are noted as a possible means of measuring absolute accuracy and long-term stability characteristics during tests on OWD equipment.

The scope of this report is limited to the results of a literature survey and initial calibration tests on a configuration for evaluation of OWD techniques and equipment. It should serve as background information and one in a series of steps toward the development of error models and performance predictions for one-way Doppler measurements on-board the Shuttle.

3.0 STABILITY TERMINOLOGY AND DEFINITIONS

The stability of a frequency standard is usually described by a statement of long term stability and a statement of short term stability. These descriptions suggest time domain definitions. Other descriptions refer to phase noise sidebands, suggesting frequency domain definitions. These two domains are related, mathematically, and are equally useful in a general description of frequency standards and their stability. In a particular application, however, one definition may be more useful than another because it has a more direct relation to a measurement method or an observable characteristic.

Several authors have provided helpful discussions[4-11] of stability definitions and terminology. Some of these discussions emphasize the importance of short-term stability because of their application to two-way Doppler systems in which a received signal can be compared, after a relatively short period of transmission, with the original source which determined the frequency of the signal. In other applications, such as time-keeping, long-term stability is more important. Both short-term and long-term characteristics should be considered in an evaluation of standards for use in making one way Doppler measurements on-board the Shuttle.

One of the most basic terms that is used in discussing the stability of a frequency source is "frequency deviation" (Δf). This is the difference between the source frequency at a particular instant (f_t), or averaged over a known interval of time, and the nominal (f) or mean frequency (f_m) of the source. Measured or computed frequency deviations are often normalized with respect to the nominal or mean frequency and then referred to as fractional frequency deviations (F).

$$F = \frac{f - f_t}{f} = \frac{\Delta f}{f} \tag{1}$$

Both long-term and short-term deviations can be illustrated by the use of Figure 1. Units of time and frequency are indicated in Figure 1, but are not defined. This permits the use of the illustration without regard for a strict line of demarcation between long-term and short-term deviations. Consider, now, this illustration to represent the frequency reference on-board a Shuttle. At launch, the frequency has the initial (f_0) value indicated. The frequency has a relatively short-term fluctuation and an upward drift which can be called a long-term instability. After t_n intervals of time, a long-term average frequency can be identified. If the long-term drift has been investigated for this particular reference and has been found to be reasonably predictable, this drift could be removed by computations within the navigation computer. Alternatively, periodic corrections could be made to the oscillator frequency throughout the flight. In either case, the deviation of

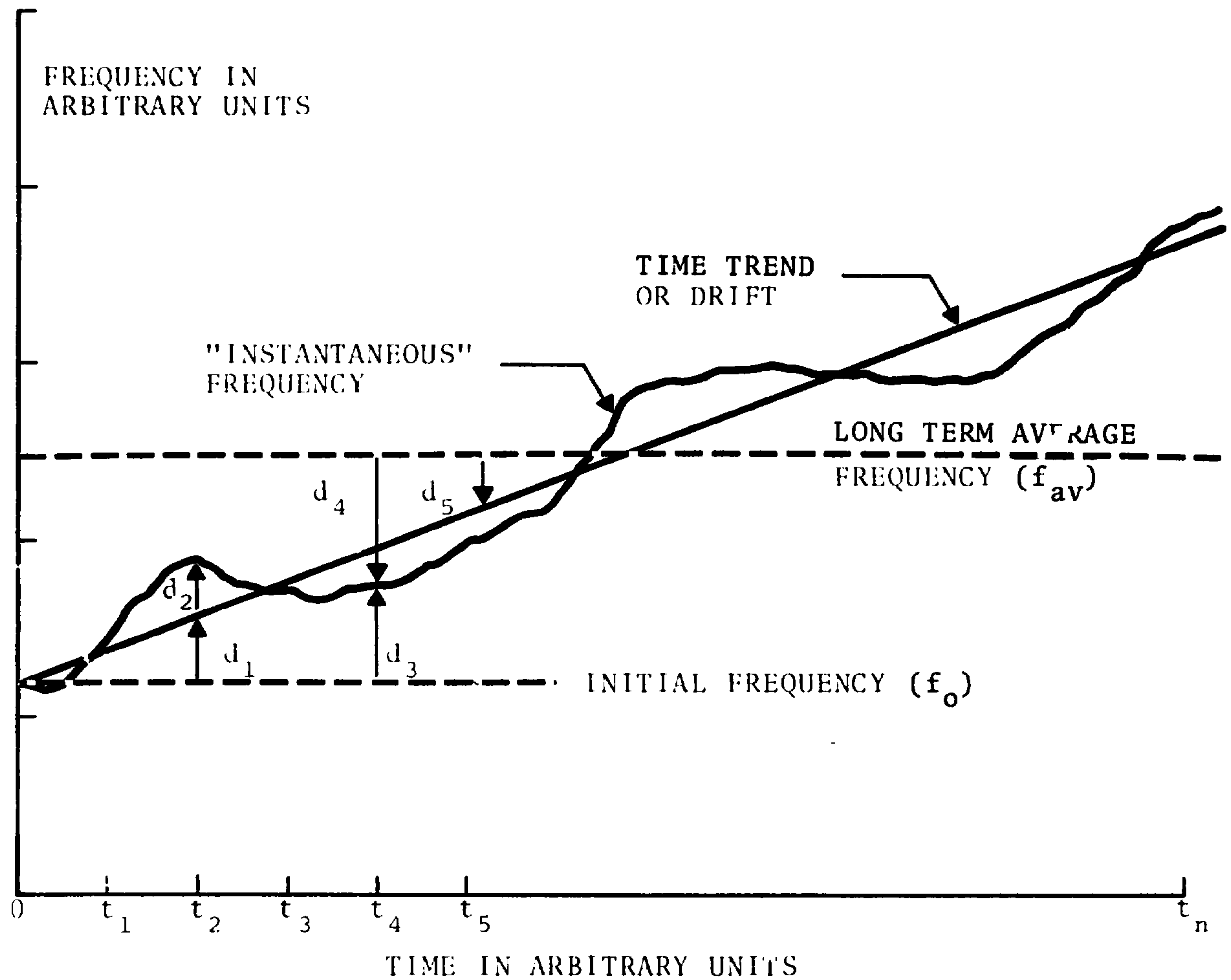


Figure 1. — A graphical representation of frequency stability terminology in the time domain.

the trend line from the initial frequency line, as noted at t_2, could be corrected by adding a predictable frequency change to the initial frequency.

Throughout the Shuttle flight, the actual frequency will fluctuate around the trend line. To discuss this fluctuation, it will be convenient to define a deviation (d_2) from the trend line. A statistical description of this deviation will be useful in predicting Doppler measurement errors if a trend line computation or correction is made on-board the Shuttle. Alternatively, a long-term average frequency might be predicted for a flight. In this case, a statistical description of the deviation (d_4) of the actual frequency from the long-term average frequency would be needed. In the simplest case, the initial frequency would be used as the reference throughout the mission. A statistical description of the deviation (d_3) from this initial frequency would then be used to estimate Doppler measurement errors from this source.

It will be convenient to have an expression for frequency as a function of time, f(t), for a particular source. Acceptance of a straight line approximation to the long-term drift permits the following expression to be written.

$$f(t) = f_0 + \alpha_f t + n_f \qquad (2)$$

The slope of the trend line in Figure 1 is introduced as α_f and n_f is the noise-like fluctuation of frequency, around the trend line. The random nature of n_f prevents the writing of a completely deterministic description for the frequency as a function of time. The fluctuating frequency term (n_f) can, however, be described in terms of statistical parameters which can be estimated from laboratory measurements.

3.1 A TIME DOMAIN DESCRIPTION OF SHORT-TERM FREQUENCY STABILITY.

Some frequency standards have a negligible long term deviation (represented by d_1 and d_5 in Figure 1) and others have this quality over relatively short time intervals. Consider, then, either of these two classes of oscillators and the need to define the Shuttle frequency reference source over a relatively short interval of time. During this interval, Doppler cycles are to be counted. For the time interval to be used here, the long term drift (d_1, d_5) can be neglected. Alternatively, it can be assumed that this long term component of deviation is correctly predicted and removed. The short term deviation (d_2), averaged over the period of interest is

$$\Delta f_{av} = \frac{1}{(t_3 - t_2)} \int_{t_2}^{t_3} d_2 \, dt \qquad (3)$$

It is assumed here, for convenience, that the counting interval is from t_2 to t_3 (Figure 1). The rms value of the short term deviation, over this counting interval, is

$$\Delta f_{rms} = \left[\frac{1}{(t_3 - t_2)} \int_{t_2}^{t_3} d_2^{\,2}\, dt \right]^{1/2} \tag{4}$$

Equations 3 and 4 can be used to define average and rms fractional deviations (F_{av}, F_{rms}) by dividing Δf_{av} and Δf_{rms} by the nominal or mean frequency (f).

Time domain descriptions are also written[7] as a function of the phase noise term in the following expression for the signal, $e_s(t)$, from a frequency standard.

$$e_s(t) = [A + a(t)] \cos [\omega t + \varphi(t)] \tag{5}$$

The amplitude mean and amplitude fluctuations (amplitude noise) are represented by A and $a(t)$, respectively. Amplitude fluctuations are not of first order significance in this consideration of frequency and phase stability and will not be given further attention at this time.

The bracketed phase term in Equation 5 is a function of time (t) and the nominal frequency (f), since $\omega = 2\pi f$. It is also a function of the short-term frequency fluctuations, $\dot{\varphi}(t)$. A theoretical expression for instantaneous fractional frequency deviation,

$$y(t) = \frac{\dot{\varphi}(t)}{\omega}, \tag{6}$$

has been used[7] as a basic time domain description. A sampling procedure is generally used to obtain a practial measurement of $y(t)$ and the sample collection requires an observation time (τ). An average value for $y(t)$, over the period of measurement is written as

$$\bar{y}_k = \frac{1}{\tau} \int_{t_k}^{t_{k+\tau}} y(t)\, dt \tag{7}$$

for kth period of τ seconds duration. A formal definition for stability is the infinite time average of the sample variance of two adjacent averages of $y(t)$. This definition[8], called the

$$\sigma_y^2(\tau) = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle, \tag{8}$$

Allan variance, implies an infinitely long data record. However, a good estimate of stability is generally considered to be obtainable by use of a limited data record of m sample differences.

$$\sigma_y^2(t) \approx \frac{1}{m} \sum_{k=1}^{m} \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \tag{9a}$$

This sum of squared deviations is obtained by subtracting the first sample from the second, then the second from the third and continuing in this manner until m deviations are processed. Another expression (9b) for $\sigma_y^2(t)$ pairs the first and second samples, then the third and fourth, using each sample in only one deviation computation.

$$\sigma_y^2(t) = \frac{1}{2N} \sum_{i=1}^{N} (\bar{y}_{2i} - \bar{y}_{2i-1})^2 \qquad (9b)$$

A more general expression (9c) is sometimes used(4,8) for $\sigma_y(t)$. Whereas (9a) and (9b) are formed by use of two adjacent samples, (9c) uses a sequence for which N is greater than 2. This is a more general form of the Allan variance.

$$\left\langle \sigma_y^2 (N, T, \tau) \right\rangle = \left\langle \frac{1}{(N-1)} \sum_{n=1}^{N} \left(\bar{y}_n - \frac{1}{N} \sum_{k=1}^{N} \bar{y}_k\right)^2 \right\rangle \qquad (9c)$$

3.2 FREQUENCY DOMAIN DESCRIPTIONS AND THEIR RELATION TO THE TIME DOMAIN

The work of standardization committees and references which propose standards(7,8) refer to the frequency domain description as the "first definition of frequency stability". The time domain description is called "the second definition of frequency stability". The first definition of frequency stability (frequency domain) is said to be the one-sided spectral density of the fractional frequency fluctuations, expressed on a per hertz basis. Although it is theoretically possible to do so, an aging rate is not generally described in the frequency domain. Other types of noise, however, such as thermal noise, shot noise, and flicker noise, are readily described by frequency domain expressions for the one-sided, noise spectral density.

A similarity has been noted[8] between some of the methods used to measure stability in the frequency domain and methods used to make stability measurements in the time domain. A spectrum analyzer is used, of course, to provide a frequency window for frequency domain measurements. A gated counter provides a time window for time domain measurements. Generally speaking, stability measurements are made by use of phase or frequency discriminators, by use of a spectrum analyzer or a wave analyzer, or by use of a counter. Phase detector recordings and records of cycle counts over known time intervals provide the most direct measure of stability in the time domain. In either of these cases, the measurement may be interpreted as a measure of the random phase noise, $\varphi(t)$, in Equation 5.

The autocorrelation function of the phase of a wave is defined to be an infinitely long time average,

$$R_\varphi(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T \varphi(t + \tau)\, \varphi(t)\, dt, \qquad (10)$$

which is adequately approximated[4] by a computation from a sufficiently large number of measurements.

$$R_\varphi(t) = \frac{1}{N}\sum_{k=1}^{N} \varphi_k\,(t + \tau)\;\varphi(t) \qquad (11)$$

Since autocorrelation functions and power spectral densities are Fourier transform pairs, the phase spectral density can be written as

$$S_\varphi(f) \;=\; \int_{-\infty}^{\infty} R_\varphi(\tau)\; e^{-j2\pi f_t \tau}\; d\tau \qquad (12)$$

The corresponding one-sided spectral density is

$$S_\varphi(f) \;=\; 2\int_{0}^{\infty} R_\varphi(\tau)\;\cos\,(2\pi f_t \tau)\; d\tau \qquad (13)$$

Differentiation in the time domain corresponds to multiplication by $j2\pi f_t$ in the frequency domain. An expression for frequency power density is obtained, then, as

$$S_{\dot\varphi}(f) \;=\; (2\pi f_t)^2 \;\; S_\varphi(f) \qquad (14)$$

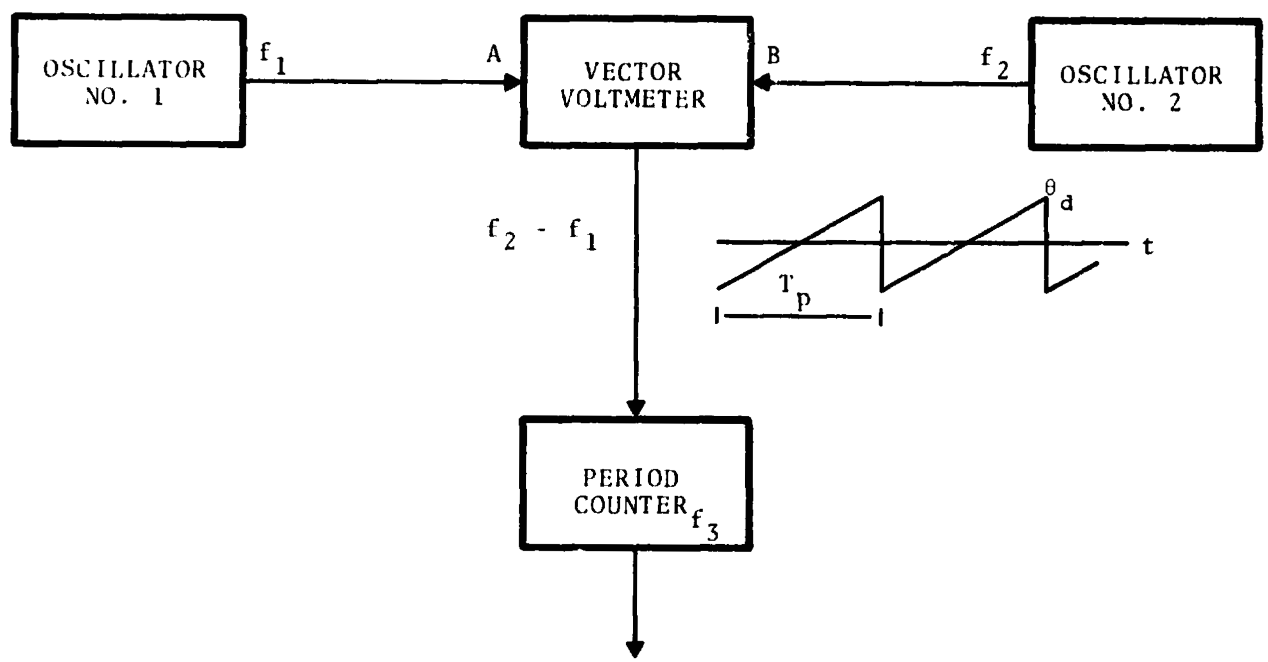
This power spectral density of the frequency fluctuations is normalized to obtain the power spectral density of the fractional frequency fluctuation with respect to the nominal frequency.

$$F = S\,(f) \;=\; \frac{f_t^{\,2}}{f^2}\; S_\varphi(f) \qquad (15)$$

Fourier transformations will, then, permit time domain measurements and relations to be described in the frequency domain. Conversely, frequency domain data and relations can be described in the time domain. In spite of the equivalence between time and frequency domains, Reference 8 states "in order to have a comprehensive and sufficient measure of frequency stability, it is preferred that the measurements involve both frequency and time domain techniques". Time domain averages of 1 to 100 seconds correspond to 1 to 0.01 Hz offsets from the carrier in the frequency domain. Special attention must be given to spectrum analyzer resolution when measurements are to be made in this region. Counters, however, are easily gated for this range of time averaging. Because time domain measurements will be easier to make over this range of averaging periods, emphasis will be placed on this approach at this time.

3.3 MEASUREMENTS WITH A TIME DOMAIN CONFIGURATION

The configuration of Figure 2 has been used to obtain stability data for several oscillators with different stability specifications. The vector voltmeter (HP 8405A) measures the amplitudes and phase difference for two input signals. An output voltage that is normally used for recording the phase difference is, in this application, used to start and stop the period counter (HP 5245L). If the two frequencies (f_1 and f_2) were exactly the same, the phase difference would not change with time.



$$N = f_3 T_p = \frac{f_3}{f_2 - f_1}$$

Figure 2. – A configuration for measuring frequency difference periods and the period fluctuations.

In this case, the voltage at the input to the period counter would be constant and the counter would not start or, if it were counting, it would not stop. The usefulness of this configuration depends, therefore, on the existence of a small difference between the two oscillator frequencies.

Consider, as an example, that the oscillator frequencies differ by 0.1 Hz. The period of the phase difference versus time wave is, in this case, 10 seconds. The counter clock frequency is, nominally, 1 MHz. The phase difference (θ_d) between the two oscillator signals increases at a constant rate, or decreases at a constant rate, if the two frequencies are constant.

$$\theta_d = 2\pi(f_2 - f_1)t \qquad (16)$$

The vector voltmeter is designed to provide an increasing voltage when the frequency of the input to Channel B is higher than the frequency of the input to Channel A. Full scale indication results for a phase difference of plus or minus 180 degrees. The voltage ramp increases from a minimum value for $\theta_d = -180°$ to a maximum value for $\theta_d = +180°$. It then drops abruptly to the -180° indication and continues increasing at the constant rate.

When the $\theta_d(t)$ wave initially drops from +180° to -180°, the period counter is started. On the next drop, the counter is stopped. The count that is accumulated is

$$N = f_3 T_p = \frac{f_3}{f_2 - f_1} \tag{17}$$

and is measure of the period, T_p. During this period, the phase difference has changed by 360° or 2π radians. From a rearrangement of (17), then,

$$(f_2 - f_1) = \frac{1}{T_p} \tag{18}$$

The measurement of N, as defined by (17), is, nominally, in microseconds. The accuracy of this measurement is dependent upon the accuracy of the clock that generates the f_3 frequency. A summary of the stability specifications for the HP 5245L clock are included in Appendix A. As noted there, a measurement over a period of 10 seconds should not be affected by the aging rate, but short term frequency fluctuations will normally occur within this period. A temperature change of one degree will cause a systematic frequency shift that will be comparable to the short term frequency fluctuations. Line voltage changes of several percent would cause systematic changes of this same order of magnitude. Collectively, these effects could cause a frequency change of about 1 part in 10^9 which is 0.001 Hz for the 1 MHz clock. The net effect for a 10 second measurement could be 0.01 Hz. Since this is beyond the resolution of the

8 digit display, it will not affect the measurement. Similar reasoning leads to the conclusion that a clock frequency inaccuracy of less than 0.1 Hz will not affect the measurement for a 10 second period. The normal error of one count will, however, cause an error in the eighth digit.

A typical period measurement of T_p = 8.115878 seconds was made with the configuration of Figure 4, using a synthesizer driver (HP 5110B) as a source of f_1 and the counter clock as a source for f_2. The counter clock also served, of course, as a source for f_3. The frequency difference between the synthesizer driver and the counter clock, averaged over the 8+ second period was, then, 0.1232153 Hz. The next measurement was 8.119960 seconds, giving an average frequency difference of 0.1231533 Hz. The difference in the two frequency measurements is 0.000062 Hz. This is a 6 part in 10^{11} fluctuation in the frequency difference between the two oscillators. The measurement does not assign the fluctuation to either f_1 or f_2, but to the combined fluctuation of f_1 and f_2. As noted in Appendix A, this fluctuation is within the specification of the counter clock, but exceeds the specification of the synthesizer driver. As a first approximation, the fluctuation could be attributed to the oscillator that is known to be less stable. Or, if the two oscillators are approximately equal in stability, the fluctuation could be assigned to both of them, on an equal basis. A better evaluation can be had, however, by the collection of more data and by the use of statistical methods of analysis.

4.0 TIME DOMAIN DATA ANALYSIS AND EVALUATION

The Doppler measurement is to be made as a count of cycles that represent the one way Doppler shift. The cycle count will be made over some finite period of time that will be used with the cycle count to estimate an average velocity or a range increment. By its nature, then, the Doppler measurement is a measure of frequency, averaged over a period of time. Consecutive counts of Doppler cycles will be made and summed to provide an integral of the velocity, which is a sum of range increments.

The nature of the implementation and application of Doppler measurements in the Shuttle operation involves a series of data points, arrayed in time. It is normal, then, to look first at a set of data presented as a time series. Table I contains two sets (x_1, x_2, x_3,..., x_{16}) of period measurements, made with the test configuration of Figure 2. As noted to the right of each data point, the reciprocal of the measurement was taken to obtain the frequency difference between the two oscillators that were used in the test. The Σ+ symbol indicates the next operation, which is the entry of the reciprocal into a subroutine that computed the mean frequency difference ($\bar{x}$) and the standard deviation (s) for the set of 16 measurements. Next, the difference was obtained between each measurement reciprocal and the mean frequency difference. Each of these deviations from the mean was divided by the nominal frequency of the two oscillators (10^6 Hz), to obtain a value of

TABLE I - PERIOD MEASUREMENTS MADE BY USE OF

A CONFIGURATION LIKE THAT OF FIGURE 2

8.0771080	½	8.0777390	½
	Σ+		Σ+
8.0755570	½	8.0760660	½
	Σ+		Σ+
8.0778990	½	8.0774220	½
	Σ+		Σ+
8.0776040	½	8.0776350	½
	Σ+		Σ+
8.0778140	½	8.0773680	½
	Σ+		Σ+
8.0746460	½	8.0763780	½
	Σ+		Σ+
8.0765560	½	8.0774250	½
	Σ+		Σ+
8.0761860	½	8.0780860	½
	Σ+		Σ+
8.0767170	½	8.0767060	½
	Σ+		Σ+
8.0759960	½	8.0763170	½
	Σ+		Σ+
8.0754240	½	8.0764290	½
	Σ+		Σ+
8.0744870	½	8.0749170	½
	Σ+		Σ+
8.0752460	½	8.0761840	½
	Σ+		Σ+
8.0755270	½	8.0755900	½
	Σ+		Σ+
8.0749960	½	8.0770270	½
	Σ+		Σ+
8.0743260	½	8.0756170	½
	Σ+		Σ+
# 16.0000000	◇	# 16.0000000	◇
0.0000177	▲◇	0.0000132	▲◇
0.1238236	x̄ ◇	0.1238132	x̄ ◇

fractional frequency deviation. These fractional frequency deviations about the mean are plotted in Figure 3 for the data set on the left of Table I. The plot is linear in time and covers a total time of about 4.3 minutes, a period of time that could represent an orbital pass of the Shuttle at some typical ground-track distance from the transmitting ground station.

4.1 A PROBABILISTIC MODEL OF THE DATA SET

The most basic features of the configuration of Figure 2 are identical to those of the configuration that will exist during Shuttle operations. This is particularly true with regard to the test oscillators of Figure 2, which can represent the ground station standard and the Shuttle reference. Simplification of the configuration, from that of the Shuttle and a ground station to the test configuration, places emphasis on the frequency sources and the errors that they will introduce in the Doppler measurements. Information from tests with this type of test configuration will be useful in predicting the accuracy of Doppler measurements on the Shuttle. If, for example, one of the test oscillators is a ground station frequency standard and the other is a Shuttle frequency reference, the configuration can be used to obtain an estimate of the error budget contribution from these two sources.

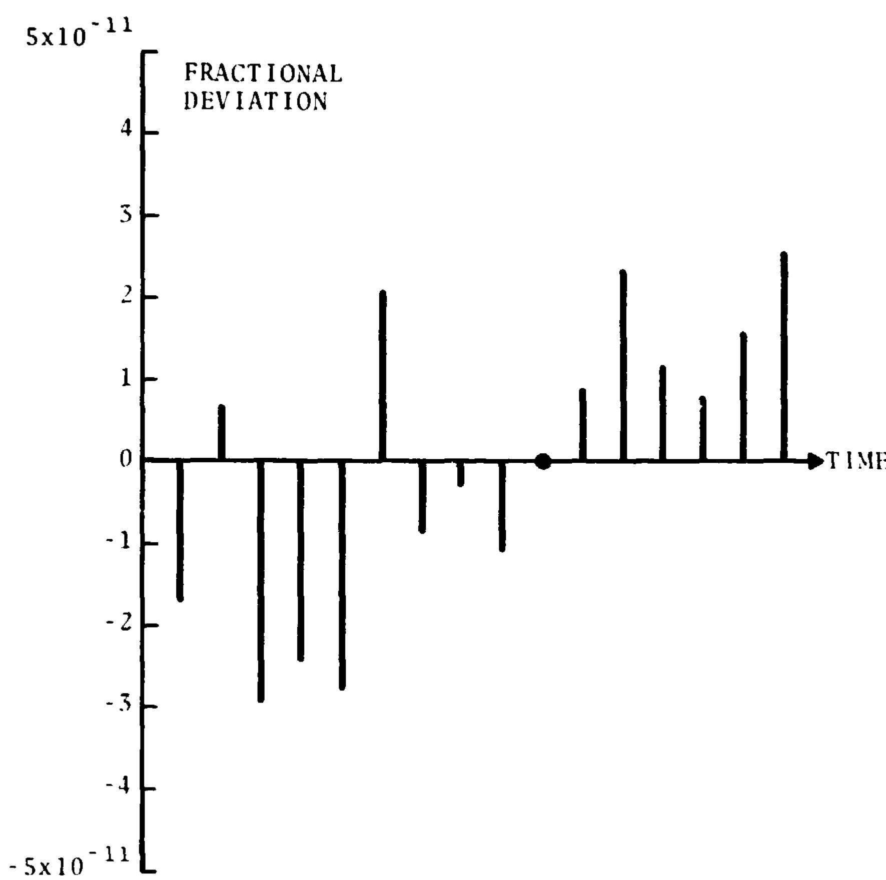


Figure 3. -- A time-series plot of fractional frequency deviations for two crystal oscillators.

A probabilistic model is needed for the fractional frequency fluctuations that are measured for the two oscillators of Figure 2 if these data are to be used in making accuracy predictions. Such a model is also important in data evaluation and in the development of a meaningful specification of oscillator characteristics. To obtain such a model, measured data were compared to a normal probability density function. The normal, or Gaussian, density function (y) was selected for first consideration because many naturally occurring noise phenomena have the characteristics of this function. The mathematical expression [12] for this function, Equation 19,

$$y = \frac{1}{\sigma\sqrt{2\pi}} \, e^{-\frac{(x-u)^2}{2\sigma^2}} \qquad (19)$$

was changed by use of the standard deviate (z) as the independent variable. Also, σ was deleted from the denominator because $dx = \sigma dz$.

$$z = \frac{x - u}{\sigma} \qquad (20)$$

The model used, then, on a trial basis, was

$$y = \frac{1}{\sqrt{2\pi}} \, e^{-\frac{z^2}{2}} . \qquad (21)$$

Day-to-day variations in the mean (u) and the variance (σ^2), and estimates of the mean ($\overline{x}$) and variance (s^2), were removed from the model in this way.

Nine sets of data, such as that on the left of Table I, were used to compare the measured frequency fluctuations with a normally distributed population. The comparison is illustrated in Figure 4. The computed mean ($\overline{x}$) and standard deviation (s) for each set were used to convert the measurements (x_1, x_2, x_3,...,x_{16}) of the set to a corresponding set of standard deviates (Z_1, Z_2, Z_3,...,Z_{16}) by use of Equation 22.

$$Z = \frac{x - \overline{x}}{s} \qquad (22)$$

Each of the 144 values of Z obtained in this way was assigned to a group that corresponds to an interval along the Z axis. The number of Z values in each interval is represented in Figure 4 by a vertical bar. The bar width represents the Z-axis interval. The smooth curve of Figure 4 is a plot of Equation 21, normalized to peak with the experimental frequency distribution.

The comparision provided by Figure 4 indicates reasonable agreement between measured data and a normally distributed population. The most significant discrepancy appears to be around $z = -0.8$. The use of more data might reduce the differences between the experimental and theoretical distributions. On the other hand, the experimental function may prove to be unsymmetrical. For example, some real physical phenomenon might skew the experimental function toward the direction of the long-term difference in the drift rates of the two oscillators.

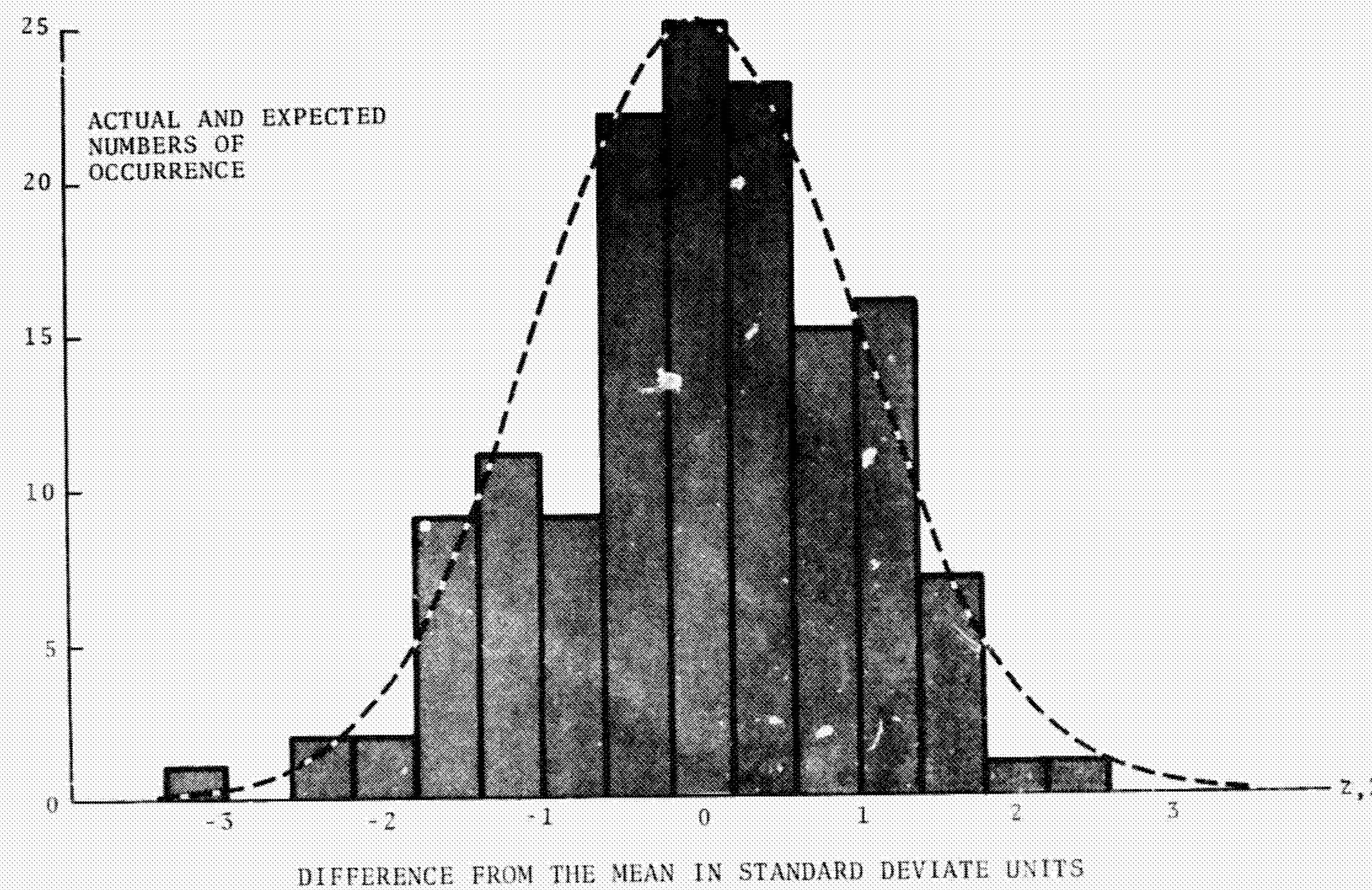


Figure 4. – A comparison of measured data with a normal probability density function.

Since the agreement between the theoretical model and the experimental data is reasonably good, a normal density function is accepted as a reasonably good model for the short-term frequency stability. The theoretical plot of Figure 4 can be used to predict the probability of experiencing fractional frequency fluctuations of a particular amplitude. For the data plotted, one standard deviate corresponds to a standard deviation of 2.889×10^{-5} Hz, or a fractional frequency fluctuation of 2.889×10^{-11}. These, then, are one-sigma values. We predict, therefore, that 68.26 percent of all future measurements of short-term stability, for these two oscillators and these conditions, will not exceed a fractional frequency fluctuation of 2.889×10^{-11}. Correspondingly, we predict that 99.73 percent of such measurements will not exceed the three-sigma value of 8.666×10^{-11}.

4.2 VARIATIONS IN VARIANCE

Three ways of computing the variance of a set of period, phase, or frequency measurements were noted in Section 3.1 and each of these may be preferrable in a particular situation. It is not clear, yet, which of these is best suited for the evaluation of Doppler measurements in the Shuttle application.

The standard deviation that is noted in Table I was computed in the conventional manner, as the square root of the variance, which is the sum of squared deviations from the mean, divided by the degrees of freedom.

$$s = \left[\frac{\Sigma(x - \bar{x})^2}{n - 1}\right]^{1/2} \tag{23}$$

The variance for the set of measurements on the right of Table I would be $s^2 = (1.316 \times 10^{-5})^2 = 1.733 \times 10^{-10}$. Using Equations 9a and 9b, the variance values for this same set of data are computed to be

$$\sigma_y^2(t) \approx \frac{1}{2m} \sum_{k=1}^{m} (\bar{y}_{k+1} - \bar{y}_k)^2 = 1.549 \times 10^{-10}$$

and

$$\sigma_y^2(t) = \frac{1}{2N} \sum_{i=1}^{N} (\bar{y}_{2i} - \bar{y}_{2i-1})^2 = 1.328 \times 10^{-10}$$

The standard deviations for these three computations are, respectively,

$$s = 1.316 \times 10^{-5},$$

$$s = 1.244 \times 10^{-5}, \text{ and}$$

$$s = 1.152 \times 10^{-5}.$$

It can be seen, intuitively, that long-term drifts will have less effect on the second and third calculations than on the first. In fact, the second and third calculations effectively remove long term drifts from the computed stability value, unless the $\bar{y}_k$ measurements are rather long term averages. This may be desirable, particularly if a specifically defined short-term stability value is needed in the application under consideration. Long-term drifts are important, however, in the Shuttle application. In this application, any period greater than the sample period, and particularly the interval between sampling instants, must be examined for long-term stability characteristics.

4.3 REGRESSIONS IN TIME

Data from Table I can be used to estimate both short-term and long-term stability. A regression, in time, can be made within the set to obtain "long-term" stability characteristics for periods in the order of several times the sample duration, in this case about 8 seconds. A regression, in time, using the means from several data sets can be used for longer-term stability estimates. The set spacing, in time, controls the period over which the stability is to be specified.

To obtain an estimate of the per-day difference in drift rates for two oscillators, data were taken over a one month period, using the circuit of Figure 2. A set of 16 or more measurements, such as those in Table I, was made at approximately the same time on 16 different days during the month. The mean $(\overline{x})$ from each of the 16 sets of data was used in a linear regression, with time in days (t_d) as the independent variable. In this way, an expression for the frequency difference (f_d) between these two oscillators was computed to be

$$f_d = 0.0605 + 0.00221\, t_d \text{ Hertz.}$$

The stabilities for these two oscillators, as specified by the manufacturer are

101A: 7×10^{-3} Hz per day

5110B: 3×10^{-3} Hz per day

Assuming these rates to be positive, as is most common for crystal oscillators, the difference in the drift rates is expected to be 4×10^{-3} Hz per day. The measured drift difference is the computed coefficient of t_d in the regression equation, 2.21×10^{-3} Hz per day.

A correlation coefficient (r) can be computed as a part of a regression analysis, to indicate the degree of the relation between the two variables. For the test just described, the correlation coefficient was computed to be 0.4133. If the two variables were completely unrelated, or uncorrelated, the correlation coefficient would have been zero. If the data points had all been on the regression line, the coefficient of correlation would have been unity. The correlation coefficient is considerably less than unity. This indicates a need for a nonlinear regression model, a random scatter of the data around the linear model, or both of these conditions.

The square of the correlation coefficient is sometimes called the coefficient of determination and is a measure of the extent to which the regression has explained the variance in the original sequence of data-set means. The unexplained, or residual, variation is $(1 - r^2)$ times the original sum of squared deviations of $\bar{x}_i$ values from their mean. The original variance for the set of means was 1.822×10^{-5}. Of this amount, $(0.4133)^2\ (1.822 \times 10^{-5}) = 3.11 \times 10^{-6}$ was explained by the regression and is considered to be a 24 hour drift rate. The residual amount, $[1-(0.4133)^2]\ (1.822 \times 10^{-5}) = 1.511 \times 10^{-5}$ is still unexplained. As noted earlier, some of this residual variance $(s_r^{\ 2})$ might be removed by a nonlinear model. Otherwise Doppler measurements made with these two oscillators would be in error by an amount that is proportional to the square root of this residual variance, $(1.511 \times 10^{-5})^{1/2} = 3.89 \times 10^{-3}$.

Another useful application of this type of regression analysis is in the evaluation of oscillator warmup (recycle) time. A linear regression on a set of measurements for a 5 MHz oscillator, within an hour after it was turned on, resulted in a correlation coefficient of 0.9999, indicating a highly time-correlated frequency. On the following day, the drift rate had decreased by more than two orders of magnitude and the correlation coefficient had dropped to 0.3368.

5.0 ENVIRONMENTAL EFFECTS OF SHUTTLE FLIGHTS

Environmental stimuli which can be expected during Shuttle flights include:

(a) vibration,

(b) shock,

(c) acceleration,

(d) temperature,

(e) radiation,

(f) supply voltage changes,

(g) magnetic fields, and

(h) electrostatic fields.

Some degree of isolation can, of course, be specified for each of these stimuli. Such isolation adds cost and weight to the Shuttle design, however, and should not be over specified. It is important, then, to define the stimuli levels and compare these with predictions of their effect on each type of frequency standard.

Current plans for use of OWD measurements on the Shuttle only require such measurements during orbital flight phases. It is assumed here that these plans include the use of OWD data during orbital maneuvers, such as orbit changes or corrections and rendezvous operations. Environmental conditions, then, are expected to involve relatively little vibration and shock during use of the OWD equipment. The equipment would, however, be required to withstand the conditions of launch, re-entry, and landing without damage and without any effects which would degrade future operation. Temperature and radiation conditions are to be controlled, to some extent, during orbital flight and during the launch and landing phases. Levels of the other stimuli noted above will probably not depend greatly on the flight phase.

Improvements in the navigation solution might be realized during launch and return to earth, as well as during orbital flight by Doppler measurements. For this reason, the effects of greater shock and vibration levels during launch and the re-entry through roll-out operations are of considerable interest. This interest, along with the possibility that high levels of shock and vibration may cause a permanent degradation of data or an effect that has a long recovery time, focuses significant emphasis on launch and re-entry conditions.

5.1 PERFORMANCE AND TEST REQUIREMENTS

Accuracy and stability specifications on the Shuttle frequency reference are significantly influenced by the system requirements for one-way Doppler measurements. Table II[14] identifies these system requirements, which include effects of ground station frequency accuracy and stability, propagation, receiver noise, Shuttle frequency accuracy and stability, and environmental conditions.

TABLE II - ONE-WAY DOPPLER SYSTEM ACCURACIES

Counting Time (Seconds)	Maximum Noise Error (Cycles, 3σ)
0.1	0.3
0.5	0.3
1.0	0.4
2.0	0.5
10.0	2.3
30.0	6.0
60.0	12.0
600.0	120.0

NOTE: Maximum Allowable Bias Error is 2 Hz for a 1 day period, at the S-Band frequency.

The effects of environmental conditions on the Shuttle frequency source are estimable through the use of stability factors that relate frequency stability to each environmental condition, along with a definition of the environmental conditions. Table III[1,16] summarizes the environmental conditions which have been specified as requirements for the Shuttle frequency source. Figure 5 defines the random vibration specification for the Shuttle as a function of frequency. Table IV[1] is a list of performance characteristics which must be met by the Shuttle frequency source. The Shuttle frequency source must meet the performance requirements of Table IV during exposure to, and after exposure to, any feasible combination of the environmental conditions noted in Table III[1].

Compliance with the long-term stability requirement, noted in Table IV is to be verified[1] by at least 100 frequency measurements. These 100 measurements are to be equally distributed over a 24 hour period. Each of the measurements is to be taken over a 100 second averaging time.

The short-term stability of the Shuttle frequency source is to be verified[1] for each of the averaging times (0.5, 1.0, 2.0, 10.0 seconds) noted in Table IV. At least 100 frequency measurements are to be made at each of these averaging times. The measurements for a particular averaging time are to be made at intervals that do not exceed one minute.

TABLE III - ENVIRONMENTAL CONDITION SUMMARY

(References 1, 16 and 17)

Environmental Condition	Requirement Specification
Vibration	11.78 g rms random vibration (see spectrum in Figure 5) for 2 hours along each axis.
Shock	Landing, one application of a 1.5 g (peak) pulse of 260 milliseconds duration. Also, more applications of lower peak and longer duration.
Acceleration	5 g for 5 minutes in both directions along each axis.
Temperature	35°F to 130°F
Radiation	None
Supply Voltage	24 to 32 volts

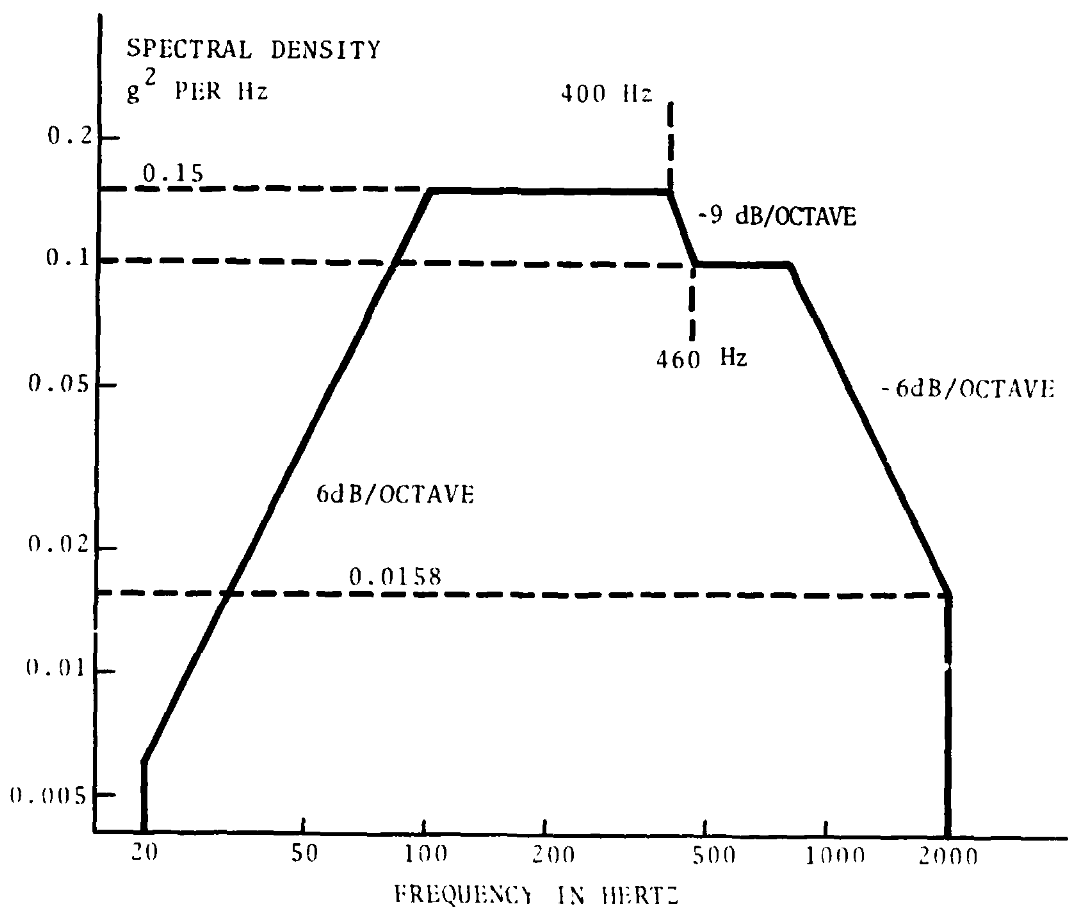


Figure 5. – Random vibration spectrum[17].

TABLE IV - PERFORMANCE REQUIREMENTS FOR
THE SHUTTLE FREQUENCY SOURCE
(Reference 17)

Performance Characteristic	Requirement Specification
Frequency	4.608 MHz
Adjustment	± 1 part in 10^7
Resolution	1 part in 10^{10}
Stability	
Long-Term	1 part in 10^9 or less over a period of 24 hours
Short-Term	1 part in 10^{10} (rms) or less for averaging times of 0.5, 1.0, 2.0 and 10.0 s.
Stabilization Time at a temperature of 30°F. (after 72 hours off)	Frequency error and drift rate shall not exceed
1 hour	$\pm 2 \times 10^{-8}$
8 hours	$\pm 7 \times 10^{-9}$
24 hours	$\pm 2 \times 10^{-9}$
Repeatability (after 48 hours off)	Within $\pm 1 \times 10^{-9}$ after 8 hours
Acceleration Sensitivity	1×10^{-9}/g or less

5.2 ENVIRONMENTAL EFFECTS ON CRYSTAL AGING

One of the disadvantages of the crystal oscillator, insofar as the Shuttle application is concerned, is a long-term drift characteristic. This drift is generally called, or attributed to, aging. Distinction is sometimes made of a related characteristic, called frequency stabilization[18]. This characteristic, stabilization, manifests itself as a relatively rapid rate of frequency change, or drift, during the first few weeks or months after production processes are completed.

The transition from a period of stabilization to the period characterized by the rate of drift called aging is gradual, rather than distinct. In fact, the drift rate history has been described[19] as an exponential function that can be extrapolated. The curves of Figures 6 and 7 illustrate this concept, following the shape and magnitude reported in Reference 19. The oscillators tested in that study showed a drift rate of one part in 10^9 per month, within the first few months of testing. Data indicated, however, that a long term rate of one part in 10^9 per year could be expected.

Several of the environmental effects, to which space borne crystal oscillators are generally subjected, might cause frequency shifts or changes in the aging rate. Two observers[20,21] have reported aging rates for an oscillator on the Timation II satellite.

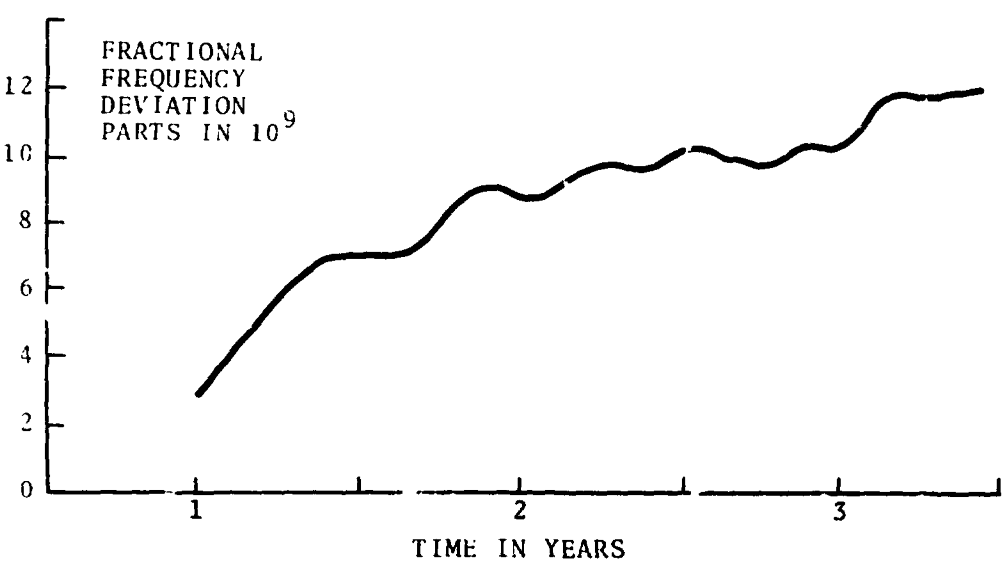


Figure 6. – Typical aging behavior for a good crystal oscillator[19].

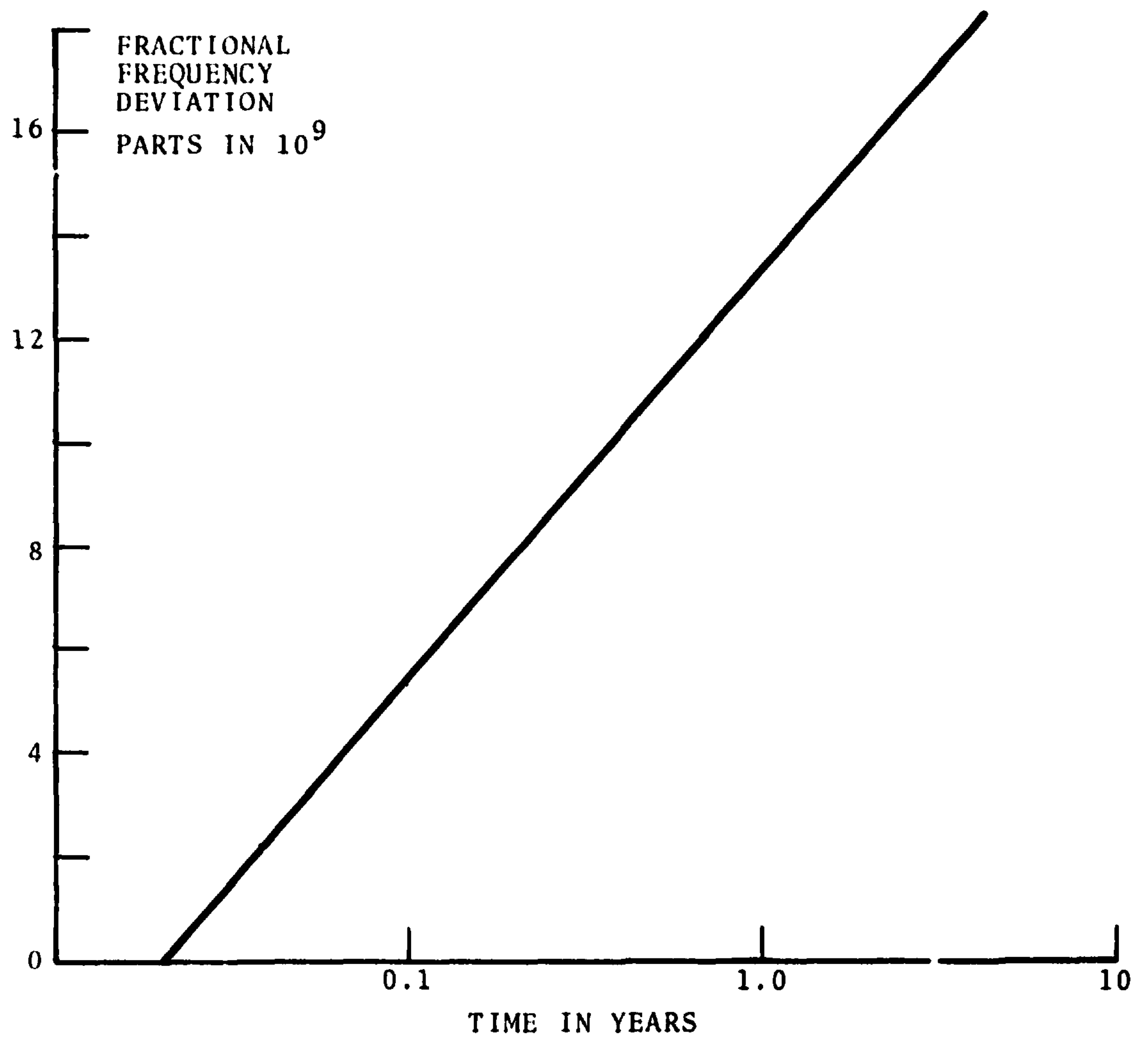


Figure 7. - A linearized approximation to the long-term drift of a good crystal oscillator[19].

Prior to launch, the drift rate was about 1 part in 10^{11} per day. During the initial period of operation in space, the rate went to a high of about 3 parts in 10^{11} per day and followed an aging rate curve with a negative slope for more than 100 days. As noted in Figure 8, the aging rate passed through zero and went as high as about 5 parts in 10^{11} per day, in a negative direction. Then, it began to decrease again at a decreasing rate. The last data reported in the reference indicate a negative drift rate of about 2 parts in 10^{11} per day. A significantly different aging characteristic was reported from Timation I. Figure 8 shows a very low and almost flat aging rate history for this oscillator.

5.3 RADIATION EFFECTS ON CRYSTAL OSCILLATOR FREQUENCY

Semiconductors are known[22] to undergo changes when subjected to radiation of the type and levels experienced during space flight. Corresponding information regarding quartz crystals has also been found in the literature reviewed. A shift in frequency has been reported[20], however, to have been caused by transient radiation. The plot of Figure 9 shows a relatively abrupt change of about 4 parts in 10^{10} in a negative direction. This change appears to have occurred over a period of about one day. The aging rate prior to, and after, the radiation occurrence appears to be in the order of 1 part in 10^{11} or less. The change, then, was by a factor of about 40.

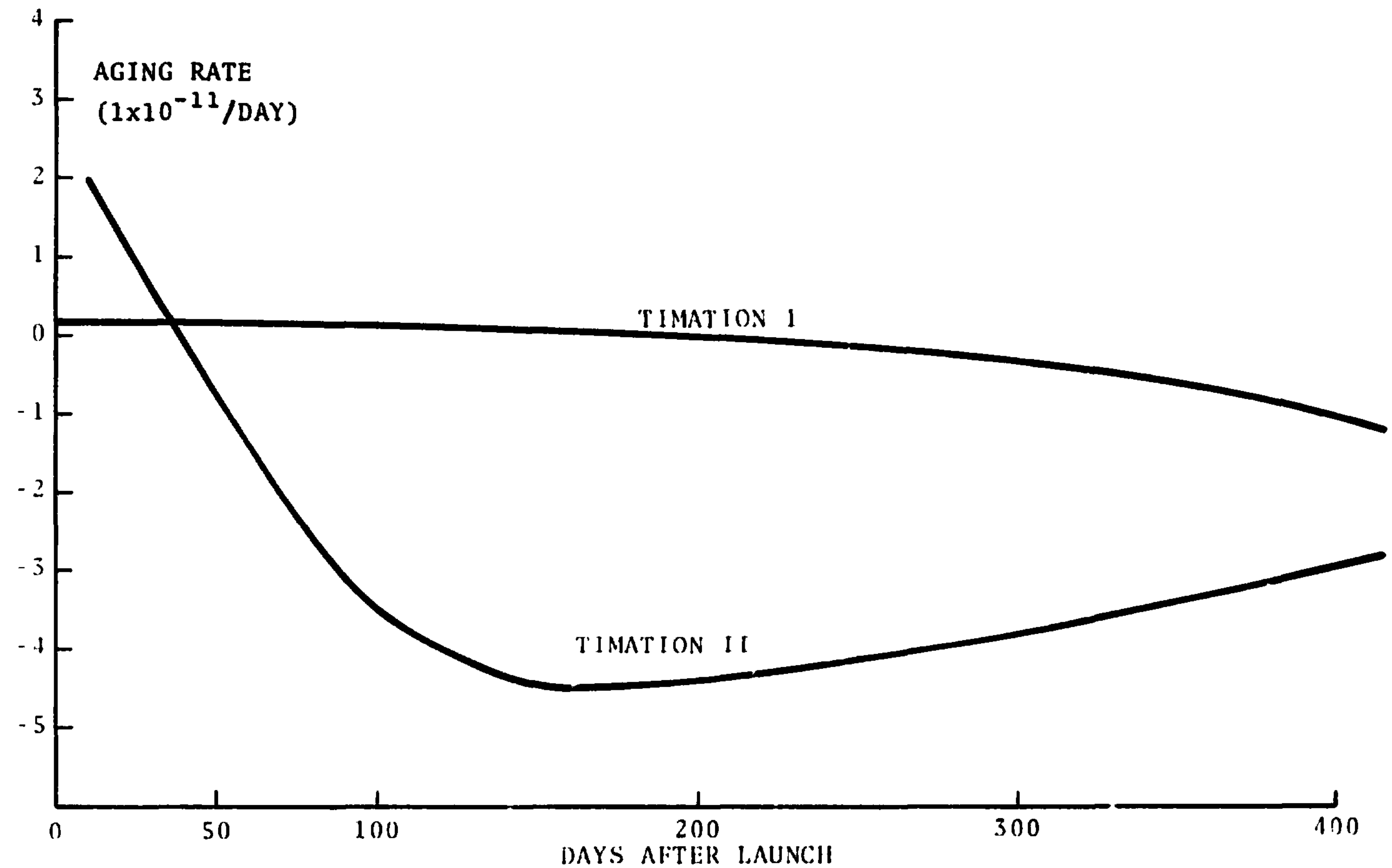


Figure 8. – Aging rate history for spaceborne crystal oscillators[20,21].

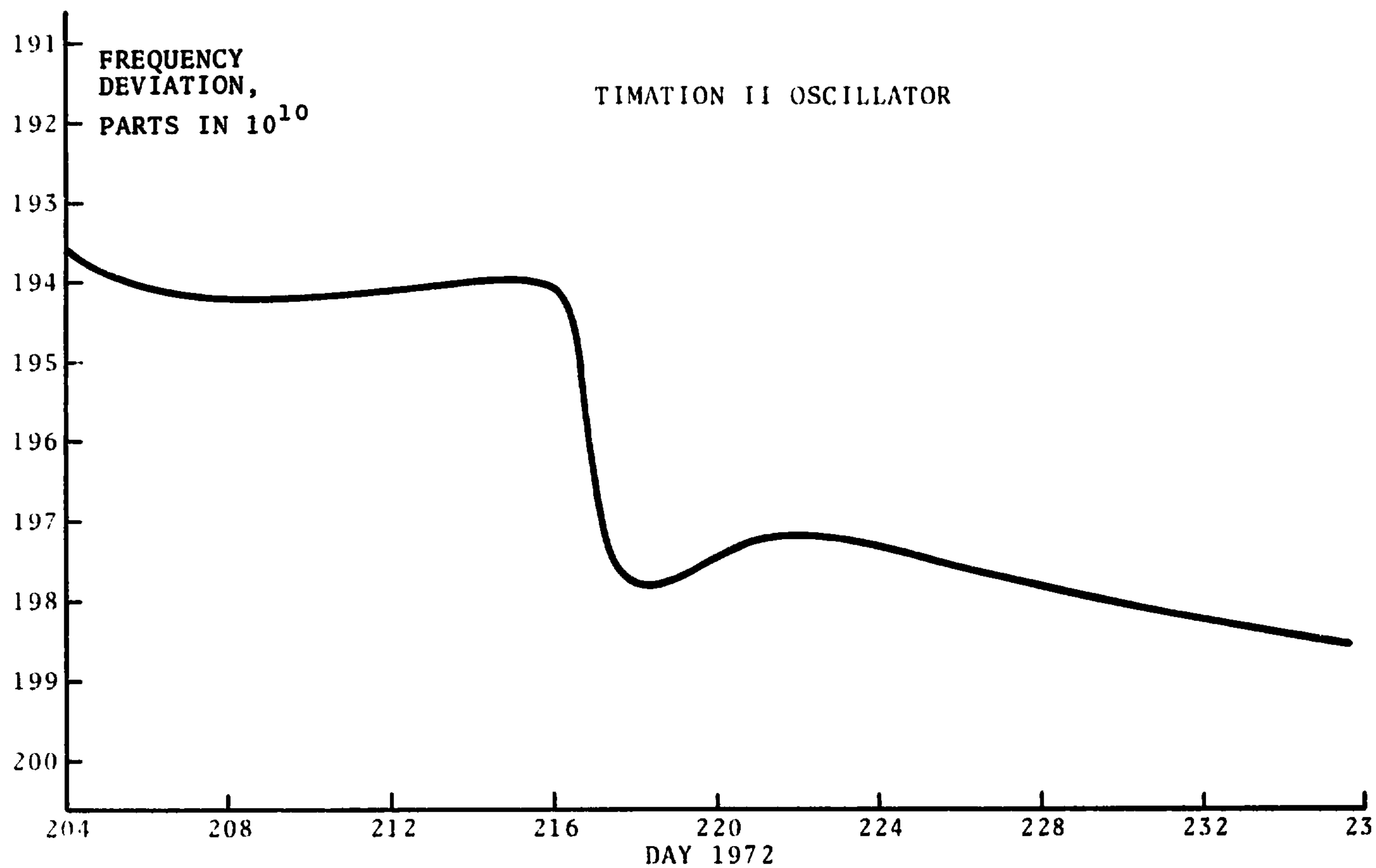


Figure 9. – Frequency shift in a spaceborne crystal oscillator, attributed to radiation [20].

According to [23], the characteristic effect of radiation on quartz oscillators is the introduction of a negative drift component. This effect has been verified in the laboratory, and should be anticipated. The reason for the better performance of the Timation I oscillator, compared to the Timation II oscillator (see Figure 8), is believed to be the counteracting effect of radiation. A normally positive aging was almost nulled by the negative aging rate caused by radiation. Because of this experience with crystal oscillators, two rubidium oscillators are to be flown on Timation III, along with one crystal oscillator. Radiation sensors are planned to obtain an estimate of the correlation between incident radiation and the aging rate.

5.4 THE IMPORTANCE OF CRYSTAL MOUNTING DESIGNS

In an effort to improve the frequency stability of crystal oscillators, Warner[19] investigated the effect of different mechanical mounting methods on the performance of an oscillator under conditions of changing temperature, shock, and vibration. The quartz crystal was plated with gold, mounted on its quiescent edge in an evacuated enclosure, and operated in a thickness shear mode. In this way, the mechanically vibrating portion of the crystal was isolated from the mounting.

An initial step in the mounting design is the enclosure of the mount in an evacuated housing. The crystals developed and tested in the Warner[19] study were housed in an evacuated glass envelope, generally cylindrical in shape. The maximum dimension of the envelope, the height, was 2 inches. The diameter of the cylinder was just under 2 inches. Findings indicated an increase of 20 or more in the Q if the crystal is housed by use of a vacuum-enclosed mounting. A maximum Q value of 10 million was measured for shaped, vacuum-mounted crystals. The maximum Q of a flat quartz plate in air was about 400,000. Plano-convex shaping was used to improve temperature-coefficient control, with no apparent loss in Q.

Three ribbon-shaped mounting elements rigidly supported the crystal with a minimum of thermally induced strain. This three-point mounting permits radial expansion of the crystal plate, but restrains the plate from translation or rotation during mechanical shock. With this new mount, the time for the frequency to recover to within a few parts in 10^8 after a step in temperature was only 2 hours. The use of rod mounting, instead of the ribbon mounting, resulted in a 12 hour recovery time. Similarly, the time required for frequency stabilization to about 1 part in 10^9 per day was about two weeks for the rod mounting and only two hours for the ribbon mounting.

Static loads as high as 200 g's, in any direction, cause no apparent movement of the crystal with respect to its mounting platforms. Severe shock, such as a four-inch drop, will dislodge the mounting, however. No permanent frequency change greater than one part in 10^9 was observed when 5 MHz oscillators, using crystals with this mounting were subjected to 10 g vibration of 2000 Hz.

Improved performance of oscillators in which this crystal and mount design was used is attributed to the relief of mechanical strain, including thermally induced strains. A gravity-induced strain was observed, however, to cause fractional frequency deviations as high as 1.5 parts in 10^9.

5.5 VIBRATION, SHOCK, AND ACCELERATION

The effects of vibration, during the launch phase, and the shock and deceleration during re-entry, are expected to require attention in the design, specification, and testing phases of the Shuttle-borne frequency reference development. Crystal oscillators are reputed[24] to have a vibration sensitivity of about 10^{-9}/g. Such a sensitivity is generally attributed to oscillators that use ribbon mounted crystals wher more specific information is not available from test data. Particular attention to the mounting technique has reduced the vibration sensitivity to about 10^{-10}/g.

When the crystal oscillator is subjected to sinusoidal vibration, sidebands are produced just as though a sinusoidal modulating source had been introduced. The modulation index increases in a linear manner with vibration amplitude over the limits of vibration reported in

Reference 24. The modulation index decreases with frequency, however, indicating a response to the modulating source that is typical of a frequency modulation process rather than a phase modulation process.

The results of tests reported in Reference 24 are illustrated in Figures 10 and 11. The crystal mount resonance frequency is a dominant feature of Figure 11. This resonance effect was unacceptable in the pulse-Doppler radar application for which the tests were performed. To overcome the problem, a flexible cable support was designed for the entire crystal oscillator. The resonant frequency of this support cable was about 10 Hz. Above this frequency, crystal vibrations were attenuated by the supporting cable to a level that decreased at a high rate with increasing frequency. The approximate transmissibility of the cable support is shown, as a function of frequency, in Figure 12.

Crystal oscillators from three manufacturers were subjected to acceleration and vibration tests at the Johnson Space Center recently [17]. The oscillators were not designed for the environmental conditions that have been specified for the Shuttle, but the performance measured is significant because it identifies the improvements that must be provided by more rugged designs.

Static performance measurements were made before the oscillators were subjected to the vibration and acceleration tests. Data from these measurements are summarized in Table V. Tables VI and VII

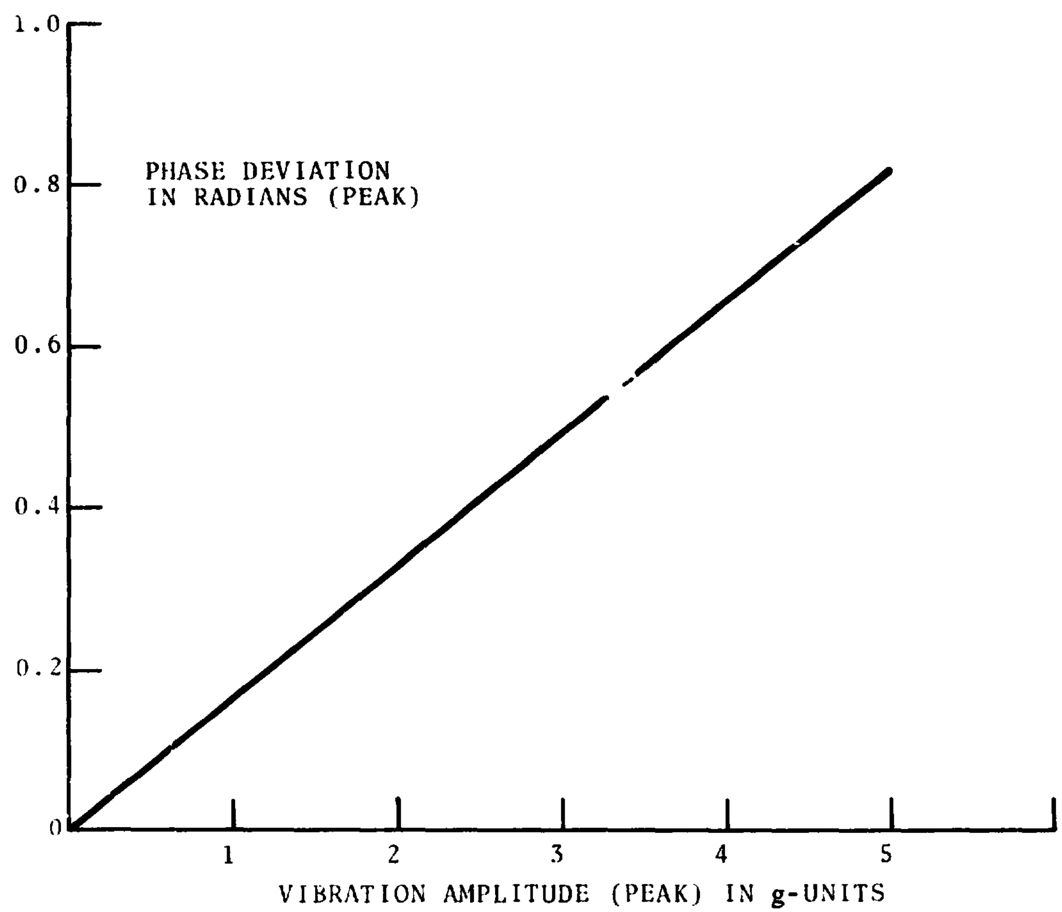


Figure 10. - Phase deviation of a crystal oscillator as a function of sinusoidal vibration amplitude[24].

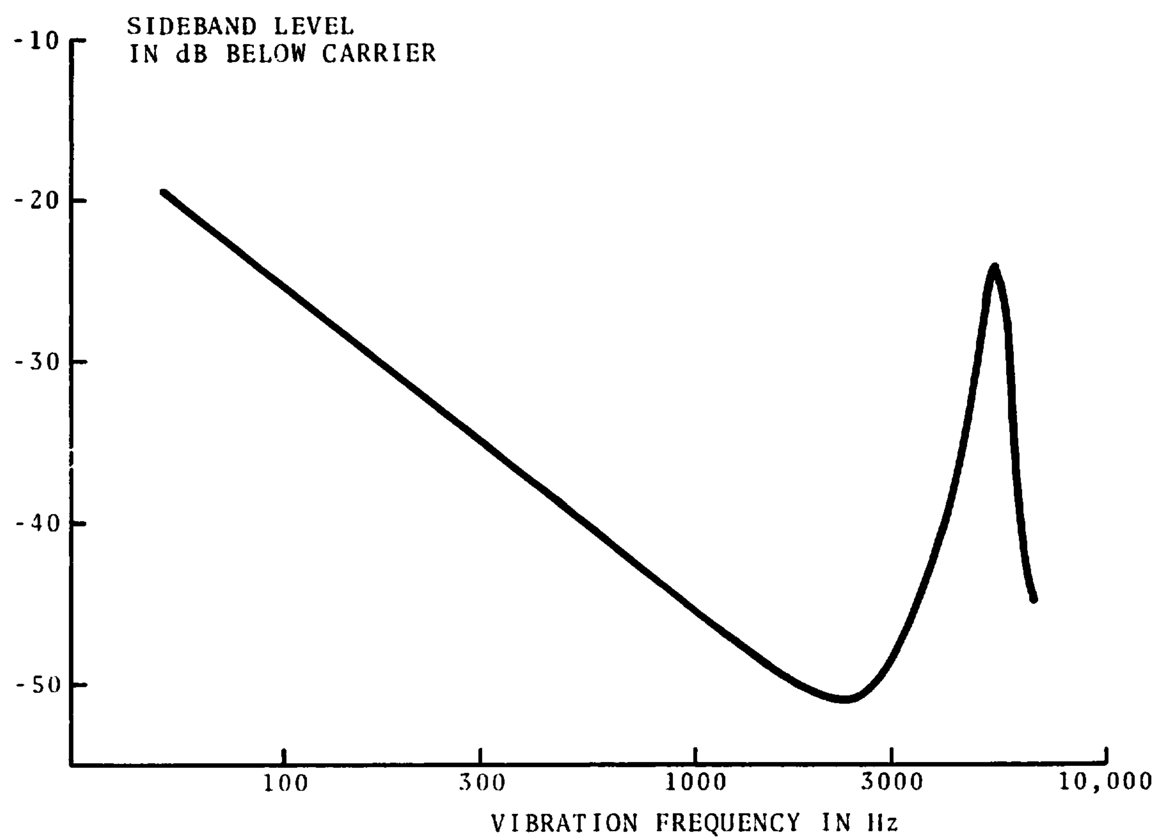


Figure 11. – Vibration sideband level as a function of frequency for sinusoidal vibration[24].

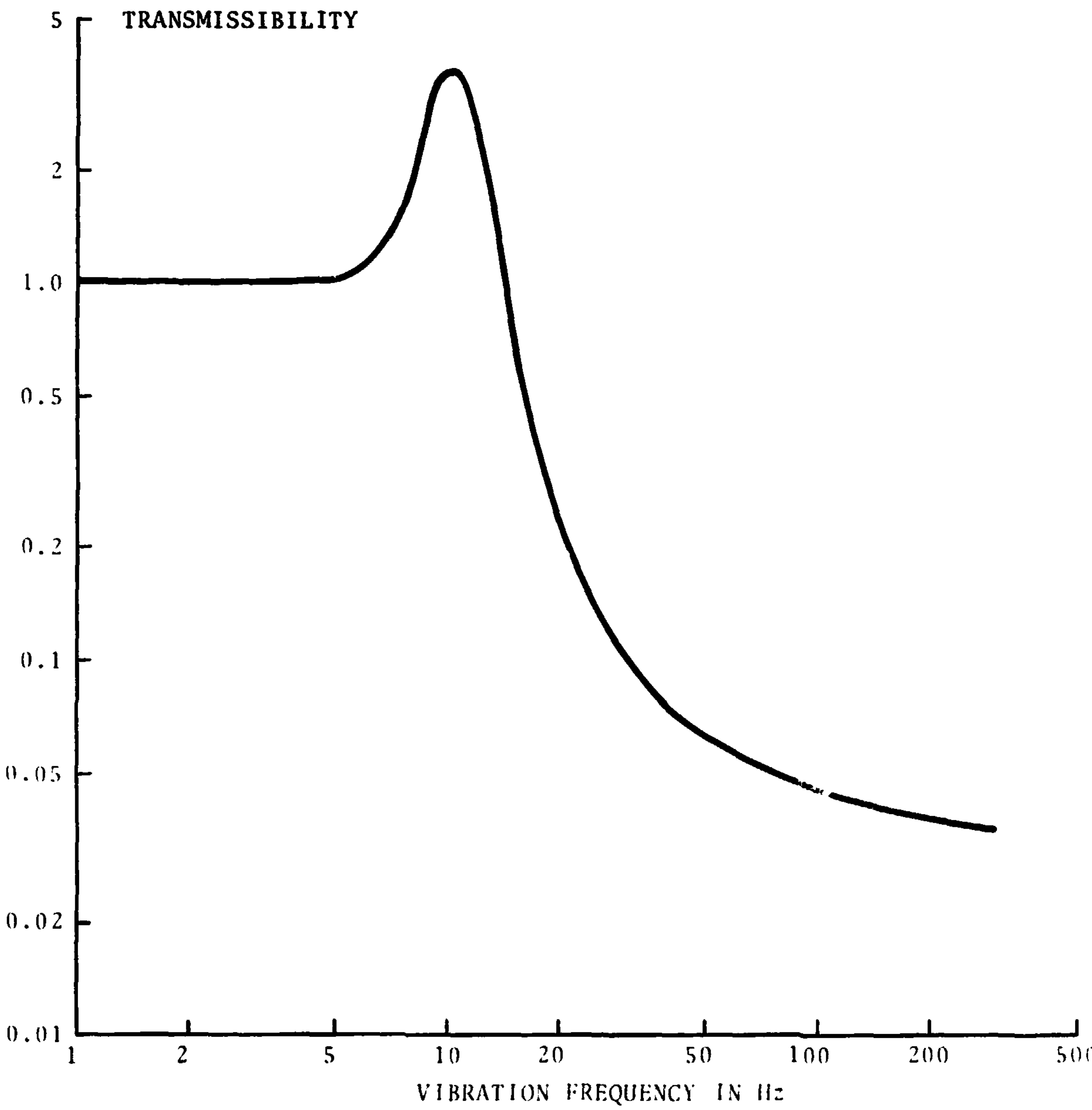


Figure 12. – Transmissibility as a function of frequency for a vibration isolation design (24).

TABLE V - TEST OSCILLATOR PERFORMANCE
PRIOR TO ENVIRONMENTAL TESTING
(Data from Reference 17)

Stability \ Oscillator Ident.	Austron 1120-1	Frequency Electronics 2037B	Greenray YH 855-1
Aging Rate, Parts in 10^9 per day	0.5	0.2	2.0
Short Term, Parts in 10^{10} for a period of			
1 second	0.18	0.16	0.32
10 seconds	0.13	0.05	0.17
100 seconds	0.10	0.03	0.40

summarize the acceleration and vibration test results, respectively. As noted in Table IV, two of the oscillators met the Shuttle specifications for aging rate (1 part in 10^9, or less, per day) and short time stability (1 part in 10^{10}, or less, averaged over a one second period). The third oscillator met the short time stability, but failed to meet the aging rate requirement.

Only one of the oscillators met the requirement for sensitivity to acceleration (1 part in 10^9/g, or less) in both directions along each axis. A second oscillator was well within the sensitivity specification on two of the three axes. The plots in Reference 17, of frequency shift as a function of acceleration, are nearly linear. Because of this, the possibility of modeling the effect and using a correction subroutine in the navigation program was suggested.

Vibration test results show a need for a vibration isolation design. None of the oscillators stayed within the required one part in 10^9 during the vibration test. One of the oscillators did, however, stay essentially within the short-term stability requirement of one part in 10^{10} throughout the vibration test. It appears that the vibration amplitude would have to be attenuated by about 26 dB to ensure a shift of no more than one part in 10^9 during vibration. If operation is not required during vibration, isolation requirements would be greatly reduced. In this case, only the offset after vibration would be considered in a vibration isolation specification.

TABLE VI - SUMMARY OF ACCELERATION TEST RESULTS
(Data from Reference 17)

Axis Along Which The Force of Acceleration Was Directed	Sensitivity, Parts in 10^9/g		
	Austron 1120-1	Freq. Elect. 2037B	Greenray YH 855-1
+ x	-0.1	+1.0	+4.0
- x	+0.3	+0.8	+2.4
+ y	+2.1	-0.7	-0.4
- y	+2.3	-0.6	-1.1
+ z	-0.5	+0.8	-1.3
- z	-0.1	+0.6	-3.3

TABLE VII - SUMMARY OF VIBRATION TEST RESULTS

(Data from Reference 17)

Axis of Vibration	Stability, Parts in 10^9		
	Austron 1120-1	Freq. Elect. 2037B	Greenray YH 855-1
Excursion peak-to-peak			
x	20	15	*
y	7	15	*
z	8	7	*
Offset After Vibration			
x	9.4	1.0	*
y	1.0	1.0	*
z	1.0	0.0	*
Short Term peak			
x	0.6	0.11	*
y	0.3	0.09	*
z	0.3	0.05	*

* This oscillator did not survive the vibration test.

5.6 ENVIRONMENTAL EFFECTS ON ATOMIC FREQUENCY STANDARDS

The most significant advantage of atomic frequency standards over a crystal standard, in the Shuttle application, is the improved long-term stability. The summary of frequency standard characteristics in Appendix B shows this advantage to be more than one order of magnitude for a rubidium standard. An even greater advantage is noted there for a cesium standard, for which the long-term drift is essentially undetectable. Little consideration need be given to other atomic standards because of size and weight disadvantages, or because of current developmental status.

Size, weight, and complexity comparisons of Appendix B are rather decisive factors, causing the cesium standard to be deleted from competition for use on-board the Shuttle. The cesium standard is of interest, however, in the evaluation of overall accuracy, which must include the effects of ground station frequency standard stability.

The rubidium standard is seen to introduce additional environmental effects, along with increased complexity. The increased complexity appears to cause little change in size and weight, compared to a crystal oscillator. It would also affect reliability, however, to some extent. Environmental effects of ambient pressure and magnetic fields are introduced, but are seen to be rather small with respect to the long-term drift specification of one part in 10^9. If future consideration is given to the use of a rubidium standard on-board the Shuttle, these sensitivities and the related ambient specifications should be used to predict error budget components.

In general, environmental sensitivities which have been observed in both crystal and rubidium standards are lower in rubidium standards than in crystal standards. Sensitivity to acceleration, for example, is about 1 part in 10^9 (or perhaps 1 part in 10^{10} for special designs) for the crystal standard and less than 1 part in 10^{11} for the rubidium standard. This implies a lower sensitivity to vibration, but data have not been found to support this conclusion. Temperature sensitivities appear to be in the same order of magnitude, with a possibility of some advantage in the direction of the crystal oscillator. Radiation effects of about 2 parts in 10^{11} for rubidium and about 4 parts in 10^{10} for crystals have been reported by the same experimenters, but under considerably different circumstances. Environmental effects on rubidium standards are described more completely in Appendix B. Also noted there is a relatively low warmup time for the rubidium standard, a possible advantage in the Shuttle application.

6.0 TIME AND FREQUENCY TRANSFERS BY RF LINK

Discussions in previous sections of this report describe feasible methods of investigating short-term stability and note the importance of both long-term and short-term stability. The absolute accuracy of the Shuttle reference frequency is also of importance, since an offset of this reference source, with respect to a ground station, will appear as a bias error in the Doppler measurement. The frequency of each ground station must, therefore, be accurately known.

The transfer of an accurate frequency reference by way of a radio link provides a method of comparing or controlling a secondary standard, or reference frequency at a remote location. Table VIII[25] summarizes the development of techniques for transmitting standard frequencies over radio links. Early broadcasts were made in the high-frequency (HF) band (3 to 30 MHz). Later, broadcasts were begun in the low frequency (LF) and very low frequency (VLF) bands because propagation conditions are more stable. In addition to the NBS media and methods noted in Table VIII, Loran C navigation transmitters and other VLF stations that are operated by the Navy provide a reference to the Naval Observatory time and frequency standards. Dissemination by satellite has also proven to be useful in recent tests.

The NBS standard uses a long-beam cesium resonance tube[25]. This standard has an estimated 3-sigma accuracy of 5 parts in 10^{12}.

A working ensemble of NBS clocks are referred to this standard and, in turn, provide frequency references and control for NBS radio broadcasts. The WWV broadcasts are controlled to a long-term average frequency that is accurate to within 5 parts in 10^{12}. Time signals, as broadcast by WWV are accurate to within 5 microseconds. The NBS station in Hawaii, WWVH, has corresponding accuracies of 5 parts in 10^{11} and 20 microseconds. VLF (3 to 30 kHz) and LF (30 to 300 kHz) stations that are operated by the NBS, WWVL (20 kHz) and WWVB (60 kHz), are accurate to within 6 parts in 10^{12}. This maximum degradation is said to occur during periods of phase correction. Broadcast accuracies, as noted here, denote deviations with respect to the standard NBS III.

TABLE VIII - SIGNIFICANT EVENTS IN THE
DEVELOPMENT OF RF TIME AND FREQUENCY TRANSFER MEDIA
(References 25, 26 and 27)

Date	Event
1923	WWV established to disseminate standard frequencies
1935	Time pulses added to WWV broadcasts
1945	Time-of-day voice announcements added to WWV broadcasts
1948	WWVH placed in operation to improve coverage
1956	WWVB began operation on 60 kHz
1960	WWVL began operation on 20 kHz
Jan 1960	All NBS broadcasts have been referenced to a cesium standard since this date
August 1962	First satellite time experiments with Telstar. (Between USNO and Royal Greenwich Observatory in England)
February 1965	Time dissemination experiments with ATS-1
1968	Initial STDN synchronization by GEOS-11
May 1968	Initial NBS use of TV time comparisons between master clocks at Fort Collins and Boulder, Colorado.
July 1970	C-Band, two-way synchronization between NASA stations, through ATS-3.

6.1 FREQUENCY COMPARISON WITH VLF SIGNALS

Radio stations NAA (17.8 kHz), NLK (18.6 kHz), WWVL (20 kHz), NSS (21.4 kHz) and WWVB (60 kHz) provide frequency reference coverage in the United States. Reception of a signal from any one of these stations permits direct control of a local reference source or a comparison measurement. The measurement, or the control, refers the local standard frequency to the frequency standards at the National Bureau of Standards and at the Naval Observatory[28,29].

Receivers used for reception of these signals generally provide a measure of the phase difference between a local standard and a phase-locked or servo-controlled oscillator in the receiver. The phase-locked oscillator can be used as a frequency source or a long-term average of the phase difference between the two oscillators can be used to control or adjust the local standard. Propagation effects may cause fluctuations of a few parts in 10^9 in the receiver oscillator frequency, but the 24 hour accuracy of a comparison measurement is reported to be about 1 part in 10^{11}.

The phase difference between a local standard and the received signal is recorded on a strip chart recorder and the change in phase difference over a 24 hour period is noted to determine the frequency difference between the local and remote standards. As an example, consider the use of a signal from NAA at 17.8 kHz. Full scale deflection on the chart is set for one cycle, 360 degrees, which corresponds to 56.2 microseconds at the signal frequency. If then, the phase difference changes by 0.08 cycles over a 24 hour period, the corresponding time is (0.08)(56.2) = 4.496 microseconds. The fractional frequency offset is this phase difference, expressed in microseconds, divided by the period over which the measurement was made, in microseconds.

$$\frac{\Delta f}{f} = \frac{\Delta t}{(\Delta T)} = \frac{4.496}{10^6(8.64 \times 10^4)} = 5.2 \times 10^{-11}$$

An increasing or decreasing phase indicates the local frequency is high or low, respectively.

Propagation time changes from day to night and is significantly variable at night. To reduce the effect of these changes in propagation time, nightime measurements should be avoided. The 24 hour measurement of the example is not adversely affected by night effects if the readings are taken at the same time during day hours. For good accuracy, initial and final phase readings are made when the entire propagation path is in the daylight.

6.2 APPLICATIONS OF LORAN-C

Much use has been made of Loran-C (100 kHz) signals for both time and frequency dissemination where high accuracy is required and where the ground wave signal strength is adequate[30]. In general, an adequate ground wave signal strength will be available within 1000 nautical miles of a Loran-C station if propagation is over land. This distance is increased to around 1400 nautical miles when the major length of the path is over sea water. Within this groundwave range, frequency resolution between 5 and 10 parts in 10^{13} has been reported. Third order servo control of a crystal standard that has high intrinsic stability has been demonstrated to better than one part in 10^{12}.

Skywave measurements with Loran-C receiving equipment have proven feasible at distances of approximately 5000 miles(31). For this radius of coverage, all major land masses of the earth are covered by usable signals, with the exception of the continent of Antarctica(32). Timing accuracies for skywave measurements, are expected to be within 100 microseconds even though the ionospheric conditions are not well known. With a one-time on-site calibration, to provide an estimate of the propagation delay, skywave timing synchronization is improved to about 10 microseconds.

In a typical remote instrumentation site, Loran-C might be used as suggested in Figure 13, for time and frequency synchronization. Two transmission paths are shown, one from the master station and another from the slave. The master station would be selected, if the signal strength is adequate, because of the more direct link to the USNO. At some locations, however, relative signal strengths may result in better measurements when the slave station signal is used.

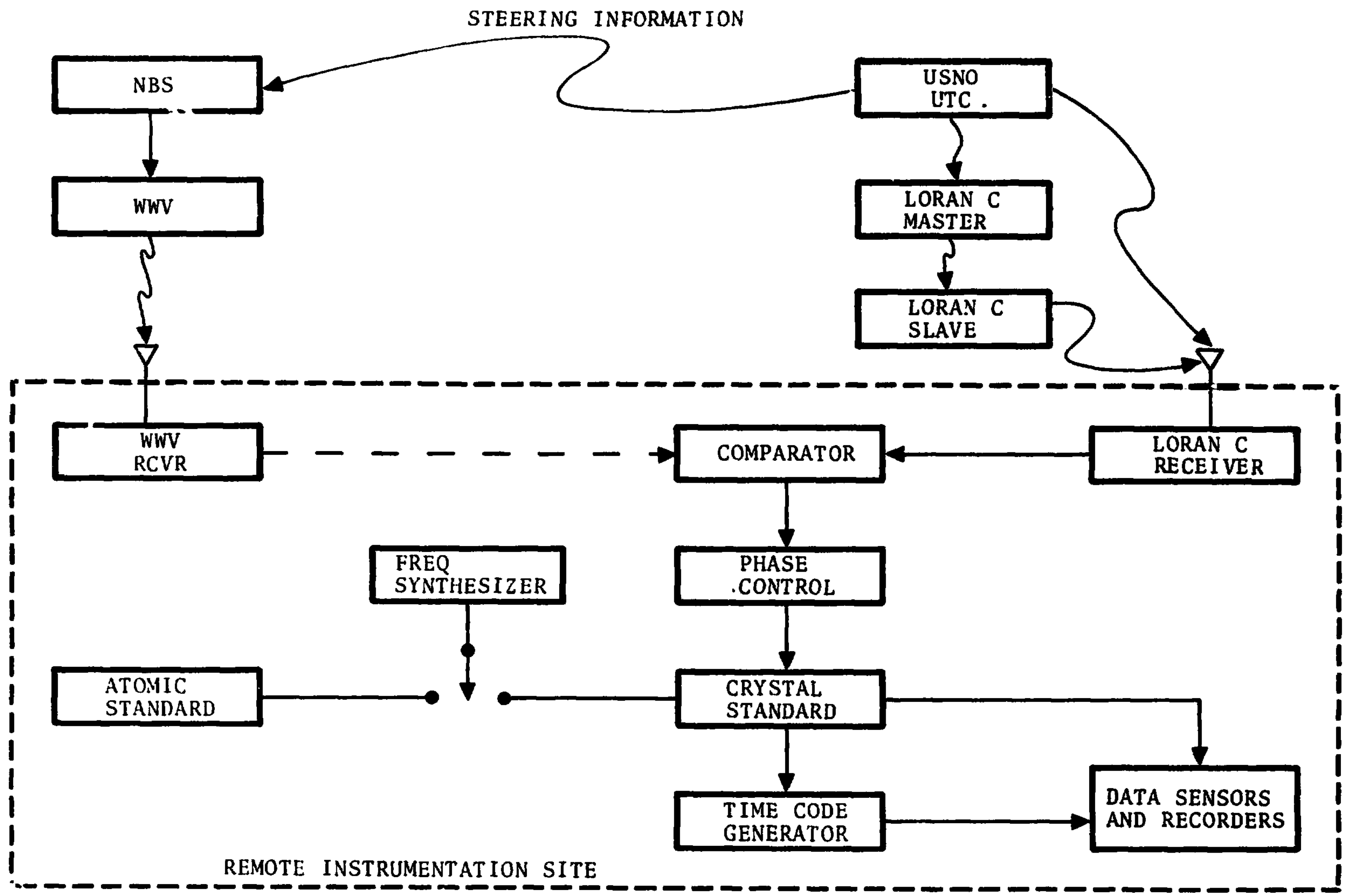


Figure 13. - Loran C frequency and time services for an instrumentation site.

Two local frequency standards are shown at the remote site although only one is needed. An option of one or the other is suggested, or the use of both for redundancy. The exact configuration will vary, of course, with the situation at each site. WWV timing is used to set the local clock to an accuracy somewhat better than a second, perhaps 10 milliseconds. A phase comparison is made between one of the standards and the time-averaged reference frequency from the Loran-C receiver. The comparison could be visual, with a manual adjustment to the frequency standard. Alternatively, the phase comparator output can be used to control the frequency standard, establishing and maintaining coherence with the USNO standard. The frequency standard output is then distributed to the time code generator for precise time interval calibrations. Time codes are recorded for time-correlation of test measurements.

6.3 SYNCHRONIZATION THROUGH TELEVISION NETWORKS

Frequency and time standards at the Newark Air Force Station (NAFS), United States Naval Observatory (USNO), and the National Bureau of Standards have been compared, for a period of several years[25], through signals from the nation-wide television networks. The comparison is made with relatively simple and inexpensive equipment which extracts the horizontal sync pulse for the tenth line of the odd field. These pulses are generated in New York City by reference to a rubidium frequency standard and are, therefore, relatively stable.

The composite TV signals are transmitted to the three stations over many microwave relays and are finally broadcast from local VHF television stations. Operations at each of the three participating stations must be accurate to within 30 milliseconds, before the time comparison is made, to avoid the ambiguity that results from the repetitive nature of the television frame structure. At a preset time, to within one second, counters are started at each of the three stations. The counters are then stopped at each station by the arrival and extraction of the odd field, tenth line sync pulse. Path delay calibration for each station and the number of high frequency clock cycles counted at each station permits the calculation of differences in the time of occurrences of the one pulse per second clock pulses which started the counters.

Measured time differences were within 6 microseconds over a period of more than a year. Typically, the mean standard deviation about the mean difference was about 0.5 microsecond over periods of one month. An improvement of about one order of magnitude is predicted for this technique through cooperative measures that could easily be taken at the originating studios, along the relay paths, and at the observers station.

6.4 SATELLITE DISSEMINATION OF FREQUENCY AND TIME INFORMATION

Relatively simple equipment is described in Reference 26 for receiving time and frequency signals from the ATS-3 satellite. This method of obtaining a long-term stability and accuracy reference was considered. A survey of related literature revealed extensive activity in this area. Two modes of operation have been practiced and experiments are continuing with both modes. One of these is passive and requires receiving equipment at the ground location, but no transmitting equipment. The other mode uses two way transmissions to obtain good measures of propagation delay.

Synchronization by one-way links from the Tactical Communication Satellite (TACSAT) has been successfully completed. Five widely separated receiving stations in North and South America were time synchronized to within 150 microseconds. Analysis of the data revealed the possibility of improving the synchronization to 75 microseconds by a priori calibration of one station with the master clock. Similar experiments with the Lincoln Experimental Satellite (LES-6) indicated an expected accuracy of 25 microseconds, through the use of these same methods.

Time synchronization of a NASA network[27], using a clock on-board GEOS-11 has also been demonstrated. In this operation, each station recorded the difference between a locally generated clock pulse and a pulse received from the GEOS-11 crystal-controlled clock. One of the stations was designated as the master and all other stations were synchronized to it by a comparison of the measured differences. In this way, the network clocks were synchronized, on an average, to within 25 microseconds of the master clock at the designated master station.

Two-way satellite synchronization experiments have demonstrated a greater accuracy than any other satellite technique, competing with the most accurate methods now under investigation. A portable cesium clock was used as a basis for evaluation in such a two station experiment. The time difference of the ground station clocks, as measured over the two-way satellite links, differed from that measured with a portable cesium clock by less than 50 nanoseconds. The significant improvement over one-way link measurements is in the propagation time calibration that is in the need for transmitting equipment at each station to be calibrated. When the relative positions of network stations are well known, however, and when these stations have somewhat similar ray paths, excellent synchronization may be possible with transmitting equipment at only one or two stations.

Satellite dissemination methods, when compared with VLF and LF dissemination, appear to require more expensive equipment and are not as well developed. In addition, the techniques appear to be oriented toward an emphasis on time dissemination. This is somewhat of a disadvantage, even though the time corrections ultimately correct the frequency standard which drives the clock.

7.0 AN ERROR MODEL FOR FREQUENCY STANDARD STABILITY

A model of frequency standard stability is needed for two purposes. First, a model is needed for use in the evaluation of Doppler extractor performance and the Doppler measurement configuration that is to be used for the Shuttle. Then, a second model is needed, simplified to reduce data processing requirements, for use in the navigation program on-board the Shuttle. This simplified model might include any effects of the ground station stability that are large enough to introduce significant navigation errors.

The model should include the elements on the right of Equation 2 and additional elements to account for environmental effects. Systematic frequency deviations should be included as functions of their causative variables. The noise term will be increased by some of the environmental effects such as vibration. To include these effects, the variance value which represents each of them will be summed with the square of n_f.

$$f(t) = f_o + \alpha_f t + \begin{bmatrix}\text{systematic}\\ \text{effects}\end{bmatrix} + \left[n_f^{\,2} + \Sigma\binom{\text{random}}{\text{effects}}^2\right]^{1/2} \qquad (24)$$

Systematic effects of temperature, line voltage and acceleration should be represented by terms in the model. Residuals from these terms should be included as random effects, along with the random effect of vibration. Stray noise, picked up by radiation and conduction, may also be significantly large. If so, it would appear as a random effect. It should be noted that the random terms may have amplitudes that vary with flight operations. Vibration is an obvious example. Stray noise may be another.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Frequency stability literature covers both frequency and time domain descriptions. Because of the range of time intervals over which Doppler counts are planned in the Shuttle application, time domain descriptions and measurements seem preferable for evaluation of the Shuttle Doppler measurements and the equipment used in making them. It may be desirable, however, to make a relatively small number of frequency domain measurements.

Methods already in use, using period counting techniques in the time domain, seem satisfactory and are similar to methods that have been reported in the literature. These methods are well suited for short-term stability measurements and can be used over a period of time to collect data from which long-term drifts can be calculated. The drifts are not calibrated, however, on the frequency axis. Such calibration appears feasible through the use of a VLF/LF receiver. By this means, the calibration can be referred to frequency standards at the National Bureau of Standards and the Naval Observatory. The procedure used would also provide a simpler, more direct and more accurate measure of long-term stability.

A survey of literature and commercial specifications shows the performance of a ruggedized crystal oscillator to be at least as good, in almost all respects as a good commercial crystal standard. In fact, performance specifications for a crystal standard that is designed for satellite service are generally better than those for commercial standards. This same trend is not so noticeable for rubidium standards, for which some degradation appears to result from an attempt to reduce size and weight.

Available information on environmental effects appears to be adequate for a first model approximation. Tests on the Shuttle oscillator will be needed, however, to refine the model. A possible exception to this conclusion regarding the adequacy of available information exists in the area of radiation effects. A radiation specification for the Shuttle is not available at this time.

9.0 REFERENCES

1. K. W. Leifeste, "Master Timing Unit Specification", Rockwell International MC456-0051, 11-5-73.

2. James C. Lamoreux, "Investigation of Error Contributions of Separate and Common Frequency Sources in Testing One-Way Doppler Extractors", TCDC Internal Note, January 1974.

3. P. L. Harton, "Preliminary Plans for Testing a One-Way Doppler Assembly", LEC-3336, April 1974.

4. Raymond E. Barber, "Short-Term Frequency Stability of Precision Oscillators and Frequency Generators", BSTJ, March 1971, pp. 881 - 915.

5. E. J. Baghdady, R. N. Lincoln, and B. D. Nelin, "Short-Term Frequency Stability" Characterization Theory and Measurement", Proc. of the IEEE, July 1965, pp. 704-722.

6. Robert B. Shields, "Review of the Specification and Measurement of Short-Term Stability", The Microwave Journal, June 1969, pp. 49-55.

7. James A. Barnes, Andrew R. Chi, Leonard S. Cutler, Daniel J. Healey, David B. Leeson, Thomas E. McGunigal, James E. Mullen, Jr., Warren L. Smith, Richard L. Sydnor, Robert C. Vessot and Gernot M. R. Winkler, "Characterization of Frequency Stability", IEEE Transactions on Instrumentation and Measurement, May 1971, pp. 105-120.

8. John H. Shoaf, "Specification and Measurement of Frequency Stability", NBS Report 9794, 7 September 1971.

9. Roy L. Chafin, "A Technique for Short-Term Oscillator Stability Measurements", Proc. of the IRE, November 1960, pp. 1914-1915.

10. Leonard R. Malling, "Phase Stable Oscillators for Space Communications, Including The Relationship Between The Phase Noise, The Spectrum, The Short-Term Stability, and The Q of the Oscillator", Proc. of the IRE, July 1962, pp. 1656-1664.

11. Jacques Rutman, "Characterization of Frequency Stability: A Transfer Function Approach and Its Application to Measurements via Filtering of Phase Noise", IEEE Transactions on Instrumentation and Measurement, March 1974, pp. 40-48.

12. William Volk, "Applied Statistics for Engineers", McGraw-Hill, 1958.

13. Samuel N. Selby and Brian Girling, "Standard Mathematical Tables", Fourteenth Edition, The Chemical Rubber Company, 1965.

14. Informal correspondence, From J. H. Dabbs to R. A. Tremant, JSC, 6/25/74.

15. Rockwell/Space Division, "Doppler Extractor", MC 478-0106-5001 (a preliminary specification), March 1974.

16. Verbal communications with Mr. R. G. Williams of the Lockheed Electronics Company, Houston, Texas, on 12 July 1974.

17. E. G. Henley, "Crystal Oscillator Test Report", LEC-3807, June 1974.

18. H. S. Pustarfi, "An Improved 5 MHz Reference Oscillator for Time and Frequency Standard Applications", IEEE Transactions on Instrumentation and Measurement, December 1966, pp. 196-202.

19. A. W. Warner, "Design and Performance of Ultraprecise 2.5-mc Quartz Crystal Units", BSTJ, September 1960, pp. 1193-1217.

20. Charles A. Bartholomew, "Timation III Satellite", Proceedings of the Fourth Annual NASA and DOD PTTI Planning Meeting, 14-16 November 1972, pp. 7-13.

21. Roger Easton, "British American Satellite Time Transfer Experiment", Proceedings of the Fourth Annual NASA and DOD PTTI Planning Meeting, 14-16 November 1972, pp. 14-28.

22. A. G. Holmes-Siedle and Karl H. Zaininger, "The Physics of Failure of MIS Devices Under Radiation", IEEE Transactions on Reliability, March 1968, pp. 34-44.

23. Telephone conversation with Mr. Roger Easton of the Naval Research Laboratory, 21 June 1974.

24. Gilbert F. Johnson, "Vibration Characteristics of Crystal Oscillators", Frequency, January 1968, pp. 30-33.

25. John B. Milton, "Standard Time and Frequency: Its Generation, Control, and Dissemination from the National Bureau of Standards Time and Frequency Division", NBS Technical Note 379, August 1969.

26. D. W. Hanson and W. F. Hamilton, "Time and Frequency Broadcast Experiments from the ATS-3 Satellite", NBS Technical Note 645, November 1973.

27. Straton C. Laios, "Satellite Time Synchronization of a NASA Network", Proc. of the IEEE, May 1972, pp. 632-633.

28. Dexter Hartke, "A VLF Comparator for Relating Local Frequency to U. S. Standards", Hewlett-Packard Journal, October 1964, pp. 1-7.

29. Verbal communications with Mr. Julian Wright of Tracor Instruments, Austin, Texas, 13 June 1974.

30. Charles S. Stone, "A Frequency Control Experiment", Technical Note 168-2, Austron, Incorporated, Austin, Texas.

31. Charles S. Stone, "A Loran-C Skywave Timing Experiment", Technical Note 168-1, Austron, Incorporated, Austin, Texas.

32. L. Dennis Shapiro, "Time Synchronization from Loran-C", IEEE Spectrum, August 1968, pp. 46-55.

33. Carroll O. Ally, Ralph Williams, Gusbax Singh, and John Mullendore, "Performance of the New Efratom Optically Pumped Rubidium Frequency Standards and Their Possible Application in Space Relativity Experiments", Proceedings of the Fourth Annual NASA and DOD PTTI Planning Meeting, 14-16 November 1972, pp. 29-40.

34. Arthur O. McCoubrey and Robert H. Kern, "Precision Frequency Sources", Proceedings of the Fourth Annual NASA and DOD PTTI Planning Meeting, 14-16 November 1972, pp. 46-54.

35. S. A. Nichols, J. D. White and R. B. Moore, "Evaluation of a Rubidium Standard for Satellite Application", Proceedings of the Frequency Control Symposium (27th Annual), Army Electronics Command, Fort Monmouth, N.J., 12-14 June 1973.

APPENDIX A

DATA FOR CRYSTAL OSCILLATOR FREQUENCY STANDARDS

The selection of transmitting and receiving frequency source types for making one-way Doppler measurements on-board the Shuttle Orbiter have been made. A significant factor in each selection was the stability characteristics of the various contenders. Simplicity was also a significant factor in the selection of a crystal oscillator for use on-board the Shuttle because of the decreased cost, size, and weight which accompany designs of lower complexity. As a general rule, simplicity also enhances reliability.

Circuit details of the Shuttle frequency reference oscillator are not yet known. In some respects, however, it is expected to be like the exemplary circuit of Figure A-1. This illustration includes most of the elements which are generally found in crystal oscillators that are intended for use as stable frequency sources.

The double oven maintains a constant crystal temperature over a specified operating range, to a tolerance of about 0.01°C. Heater current is not cycled off and on abruptly, but is smoothly controlled. Heating current is proportional to the difference between the actual and desired temperatures. Although reasonably good supply voltage regulation is expected, additional regulation is usually provided for all active elements. Automatic gain control (AGC) is used to reduce the sensitivity of the oscillator frequency to signal level changes. Both the crystal and the active elements undergo parameter

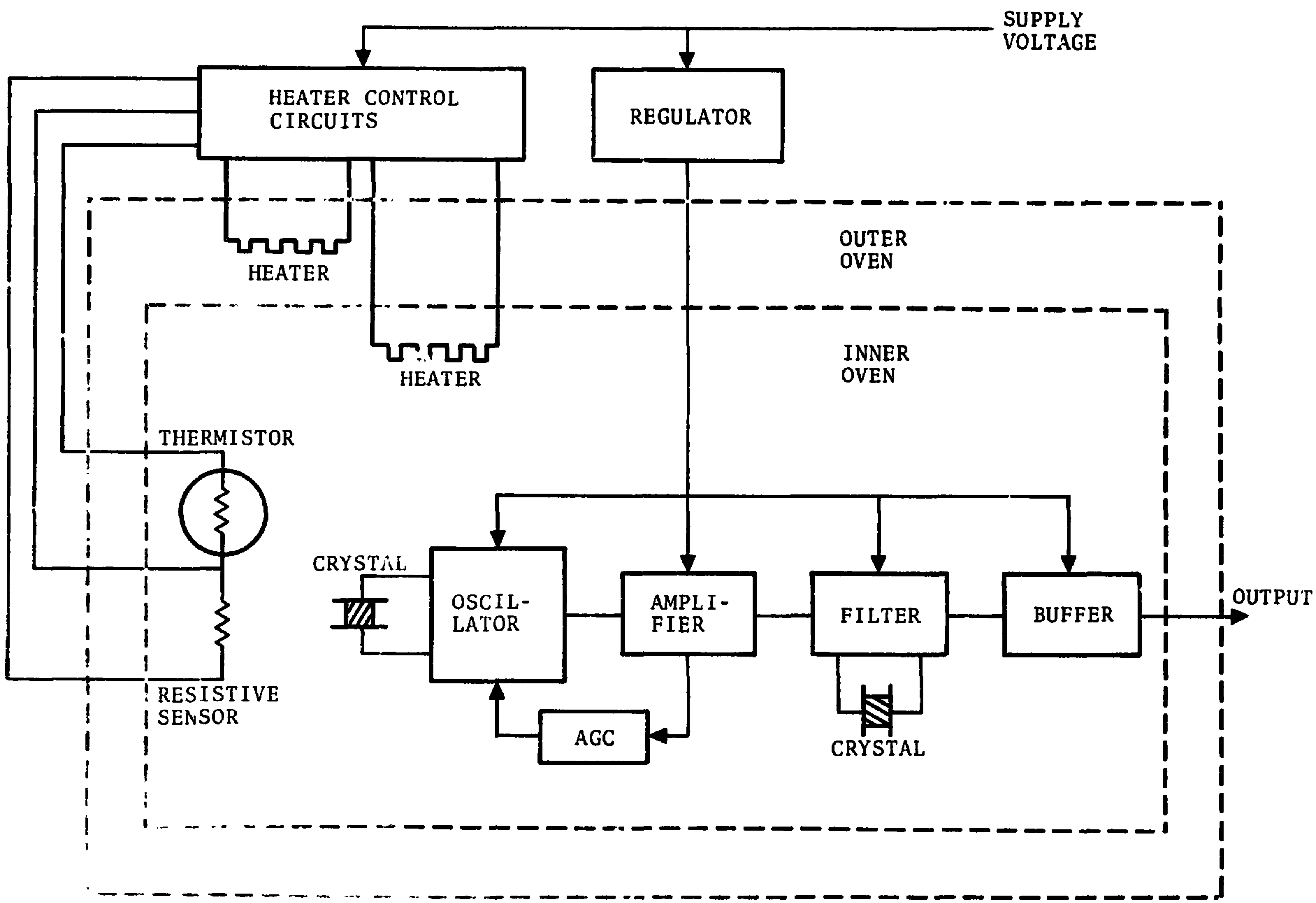


Figure A-1. – A functional illustration of an exemplary crystal oscillator.

changes as signal levels vary. Another crystal is sometimes used as a filter, following amplification which brings the signal level above the very low level of the oscillator. (Low crystal drive levels are used to improve stability.) Filtering with a second crystal reduces the noise sideband levels, particularly at frequency offsets greater than 10 Hz. A buffer amplifier isolates the oscillator from changes in loading, reducing the sensitivity of the oscillator frequency to load resistance.

All of the elements in Figure A-1 are not always included in a good oscillator design. The elements that are included in a particular design will depend, to some extent, on the application. For example, crystal filtering would not be necessary in applications where noise modulation at frequencies above 10 Hz is relatively unimportant.

Characteristics for oscillators of relatively good design are summarized in Table A-I. Only the FE 1800D is specified for space-borne applications. For this reason, information on performance in a space environment is not generally available. The FE 1800D, however, is specified to perform as well or better than other units in almost every case. It might be concluded, then, that the ruggedized design does not degrade performance. Oscillator characteristics for several test instruments are listed in table A-II.

TABLE A-I - COMMERCIAL CRYSTAL STANDARD CHARACTERISTICS

Characteristics / Oscillator Type	Austron 1120-1	Tracor 5B	Hewlett Packard HP 105 A/B	Ebauches (Switzerland) B-5400	Frequency Electronics FE 2087A	Frequency Electronics FE 1800D
Frequency, MHz	5	5	5	4-7	5-10	5
Stabilization or Retrace Parts in 10^9 (hrs off/hrs on)	10 (24/1)		1 (24/0.5)	200 (-/0.5)	20 (-/1)	
Aging Rate Parts in 10^9/24 hours	1	0.5	0.5	0.1	0.05	0.02
Short-Term Stability Parts in 10^{10} for 1s	0.3	0.1	0.05	0.007	0.02	0.008
Temperature Stability Parts in 10^9 (Temp Range in °C)	10 (-5, +55)	0.5 (-10, +60)	2.5 (0, 50)	(-60, +60)	0.5 (0, 50)	0.02 (0, 36)
Source Voltage Stability Parts in 10^9 (Input Voltage Range)	5 10%	0.2 18%	0.05 10%		0.01 2%	0.01 5%
Load Stability Parts in 10^9 (Load Variation)	1 10%	0.1 (40, 600Ω)	0.02 (0, ∞)		0.01 10%	0.01 10%
Vibration Sinusoidal Random		MIL-E-16400E	MIL-STD-167 MIL-T-21200			7g (1) 0.2g^2/Hz
Acceleration						15g
Shock			MIL-T-21200 (30g)			50g(2)

(1) From 14 to 2000 Hz
(2) 11 millisecond half sine wave

TABLE A-II. - TEST EQUIPMENT OSCILLATOR CHARACTERISTICS

Characteristics / Oscillator Type	Counter HP5245L	Counter HP5245M	Synthesizer Driver HP5110B	Synthesizer HP5105A	Synthesizer HP8660A
Frequency, MHz	1	5	1	1	10
Stabilization or Retrace Part in 10^9 (hrs off/hrs on)	3 (-/72)	0.05 (-/24)			3 (-/72)
Aging Rate Parts in 10^9/24 hours	3	0.05	3	3	3
Short-Term Stability Parts in 10^{10} for 1s	2	0.05	0.1	20	
Temperature Stability Parts in 10^9 (Temp Range in ^0C)	0.2/degree (-20, +55)	0.05/degree (0, 50)	0.2/degree (0, 55)		
Source Voltage Stability Parts in 10^9 (Input Voltage Range)	0.5 10%	0.1 10%	0.05 10%		
Load Stability Parts in 10^9 (Load Variation)		0.02 (0, ∞)			

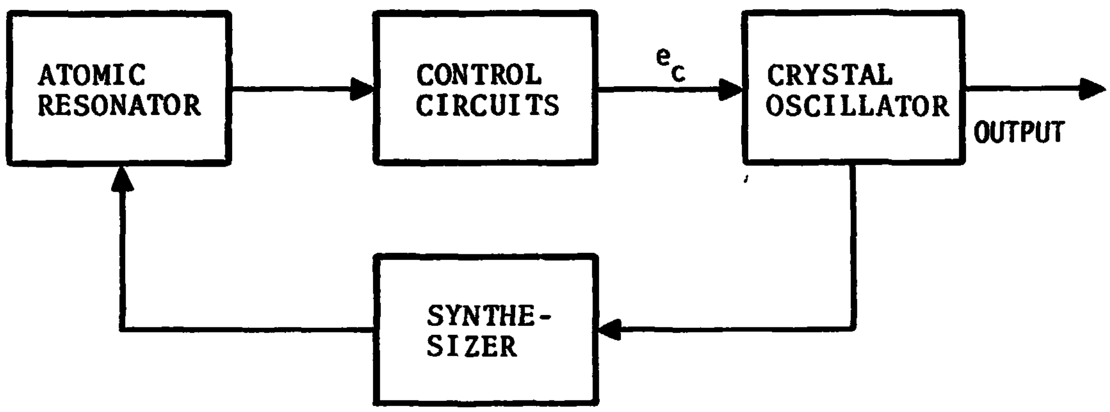
APPENDIX B

ATOMIC FREQUENCY STANDARDS

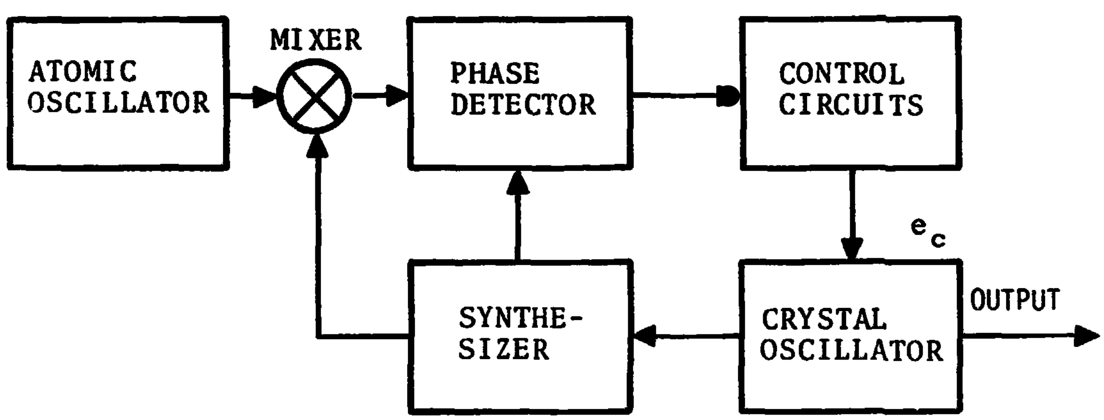
1.0 APPLICATIONS OF ATOMIC RESONANCE PHENOMENA

Two basic techniques have been used, in the development of frequency standards, which rely on the intrinsic precision of atomic phenomena. These two techniques are illustrated in Figure B-1 and, as noted there, can be distinguished by the descriptive terminology, "passive resonator", and "active oscillator". In the passive technique, an atomic device is used as a high-Q resonant circuit component to control the frequency of a crystal oscillator. Rubidium gas cells, cesium beam tubes, and thallium beam tubes have been used as the resonant elements in frequency standards of this type. In the active technique, a crystal oscillator is phase locked to a self-excited, atomic oscillator. Hydrogen masers, ammonia masers, and optically pumped rubidium masers have been used as atomic oscillators in this type of frequency standard.

Atomic resonance characteristics are centered above 1000 MHz for both passive and active devices which have been used in the design of commercial and laboratory frequency standards. The crystal oscillators that are used in these standards generally operate at 5 or 10 MHz, but sometimes as high as 100 MHz. Passive rubidium cells, passive cesium beam tubes, and hydrogen maser oscillators have proven most useful in commercial and laboratory frequency standards of recent design.



(a) Passive atomic resonator



(b) Active atomic oscillator

Figure B-1. — Essential elements for two atomic frequency standard designs.

Atomic frequency standard characteristics are compared in Table B-I. Characteristics are also listed there for a good crystal oscillator. In fact, the values listed in Table B-I are generally among the best that can be found. The minimum flicker fluctuation is an indication of the best stability that might be achieved with a given type of standard and is independent of the averaging period.

The long-term stability of atomic standards is an important advantage, compared to a crystal standard. The higher cost of atomic standards is a disadvantage, of course. For spaceborne applications, power and weight favor the crystal standard. The rubidium performance figures in Table B-I are for one of the larger units, but rubidium standards are seen to compete with the crystal standard in size.

TABLE B-I - A COMPARISON OF FREQUENCY STANDARDS

Frequency Standard Type / Characteristic	Crystal Oscillator (5 MHz)	Passive Rubidium Cell	Passive Cesium Cell	Hydrogen Maser
Long-Term Stability	2×10^{-11}/day	1×10^{-11}/mo.	Not Detectable	Not Detectable
Minimum Flicker Fluctuation	1×10^{-12}	4×10^{-13}	1×10^{-13}	1×10^{-14}
Short-Term Stability for 1s average	1×10^{-12}	5×10^{-12}	5×10^{-12}	1×10^{-13}
Temperature Sensitivity Parts/°C	5×10^{-13}	8×10^{-12}	1×10^{-13}	$<1 \times 10^{-13}$
Magnetic Sensitivity Parts per gauss	Not Applicable	1×10^{-11}	1×10^{-13}	1×10^{-11}
Required Power Watts	8	25	50	200
Cost Dollars	3,000	7,500	17,000	Not Available
Weight, kg (pounds)	2 - 15 (1 - 7)	6 - 80 (3 - 35)	147 (67)	1320 (600)
Volume, cu. m (Cubic Feet)	0.0024 (0.08)	0.001 - 0.03 (0.04 - 0.9)	0.04 (1.4)	0.465 (16.4)

2.0 RUBIDIUM FREQUENCY STANDARDS

Rubidium gas cells have been used in both active and passive frequency standard designs. As an active frequency standard element, the rubidium maser is relatively simple and compact, when compared to the hydrogen and ammonia standards. Light intensity and frequency pulling effects introduce drift and result in flicker noise levels that are somewhat higher than other masers.

Commercial designs that use rubidium gas cells have favored the passive method of frequency control. A summary of commerical rubidium standard characteristics is presented in Table B-II. Data for Table B-II have been taken from specifications provided by the four companies whose products are represented there. The FRK units have been designed and tested for space applications. Test results[33,34,35] show the ultimate long-term drift to be better than one part in 10^{10} per month after a period of stabilization. In fact, the drift was found to be "essentially zero" after an initial drift rate of about 2.5 parts in 10^{12} per day.

Sensitivity to acceleration at g-forces just above zero was found to be about 8×10^{-12} per g. The sensitivity dropped to 4×10^{-12}/g at 1g, however, and remained at this value through the maximum level (10g) of the test. This sensitivity would normally imply good performance under vibration, if mechanical resonances were adequately

TABLE B-II - CHARACTERISTICS OF RUBIDIUM FREQUENCY STANDARDS

Oscillator Type / Characteristics	Frequency and Time FRK	Efratom FRK-H	Tracor 308-A	Hewlett Packard HP 5065A
Frequency Output, MHz	10	10	5	5
Stabilization or Retrace Parts in 10^9 (minutes on)	1 (10)	0.2 (10)	0.1 (60)	0.1 (60)
Aging Rate Parts in 10^9/month	0.1	0.03	0.03	0.01
Short-Term Stability Parts in 10^{10} for 1 s	0.5	0.2	0.2	0.05
Temperature Stability Parts in 10^9 (Temp. range in °C)	1 (-25, +65)	0.4 (-25, +65)	0.1 (0, 50)	0.04 (0, 50)
Source Voltage Stability Parts in 10^9 (Input Voltage Range)	(22, 32)	0.01 10%	0.01 20%	0.004 10%
Load Stability Parts in 10^9 (Load Variation)				
Vibration				MIL-STD-167 (2)
Acceleration				
Shock				MIL-T-21200 (3)
Magnetic Field Parts in 10^9/Am^{-1}	0.001	0.001	(1)	(4)
Altitude Parts in 10^9/mbar	0.001	0.0005		(5)

(See next page)

TABLE B-II (Continued)

NOTES:

(1) 1×10^{-11} for any orientation in the earth's field.

(2) Also, curve 1 of MIL-E-5400, with isolators.

(3) Also, MIL-E-5400 (30 g).

(4) 0.005×10^{-9} for 1 gauss change.

(5) 0.05×10^{-9} for altitudes from sea level to 40,000 feet.

suppressed. Performance under vibration was not acceptable, however, because of equipment failures. Corrective designs were not believed to be extensive, but no further test data are available.

Temperature sensitivity varied for two units which were subjected to a range of temperatures from 5 to 40^{o}C. For one unit, the variation was essentially linear through a total variation of about 1 part in 10^{10}. Over a selected 5^{o} range, this unit had a $0.4 \times 10^{-12}/^{o}$C deviation. Performance o the second unit was more erratic, with a high variance around a somewhat parabolic characteristic. Over a selected 5^{o} range, it had a $0.3 \times 10^{-10}/^{o}$C deviation.

The sensitivity to ambient pressure was measured between standard atmospheric conditions and a pressure of 10^{-6} Torr. (A Torr is equivalent to 1.333×10^{3} dynes/per square centimeter or 1 millimeter of mercury. Standard atmospheric pressure is 760 millimeters of mercury. The international unit of pressure, the pascal, is equivalent to 10 dynes per square centimeter or one newton per square meter.) Over this range, the sensitivity was negative. The frequency increased 12.3 parts in 10^{10} for the decrease in pressure.

Sensitivity to radiation was relatively low. It was reasoned that this low sensitivity resulted from counter-acting effects. An expected change in the crystal was offset by a change in control voltage at the time of irradiation. A 300 rad dose was applied over a period of 10 hours, at a constant rate of 0.5 rads/minute. (A rad is equivalent to 10^{-2} joules per kilogram.) A change of -1.5 parts in 10^{11} was observed when the irradiation was begun. No further change was noted, even for a second irradiation. The effect remained evident for a period of 5 days.

Fractional frequency fluctuation over a period of one second was measured to be about 2 parts in 10^{11}. This decreased to about 1 part in 10^{12} for a 100 second period.

A comparison of the rubidium standard stabilization or warmup time with that of a crystal standard reveals what might be a significant advantage. One of the rubidium standards noted in Table B-II is specified to be within 2 parts in 10^{10} of its operating frequency after a 10 minute warmup. Crystal standard warmup time is nominally one order of magnitude greater than this, at best.

3.0 CESIUM-BEAM STANDARDS

Commercial cesium beam frequency and time standards use a cesium tube which has an electrical resonance characteristic. The phase response of this resonant element shifts the phase of a control signal that is used in a servo loop to control the frequency of a crystal oscillator.

As noted in Figure B-2, the output frequency from a crystal oscillator is passed through a synthesizer and a multiplier chain to a mixer. A phase modulated sample from the crystal oscillator is also applied to the mixer, producing a phase modulated signal at, or near, the resonant frequency of the cesium beam tube. If this signal differs in frequency from the resonant frequency of the cesium beam tube, the beam current of the tube will contain a component at the frequency of the control signal. The phase of this component of current depends on the direction of the difference between the cesium tube resonant frequency and the synthesized frequency from the crystal oscillator.

The component of cesium tube current at the control frequency is selected by a tuned amplifier and passed to a phase detector. A sample of the control frequency is also applied to the phase detector, directly from the control oscillator, as a reference for comparison with the beam tube current component. The phase difference between these two

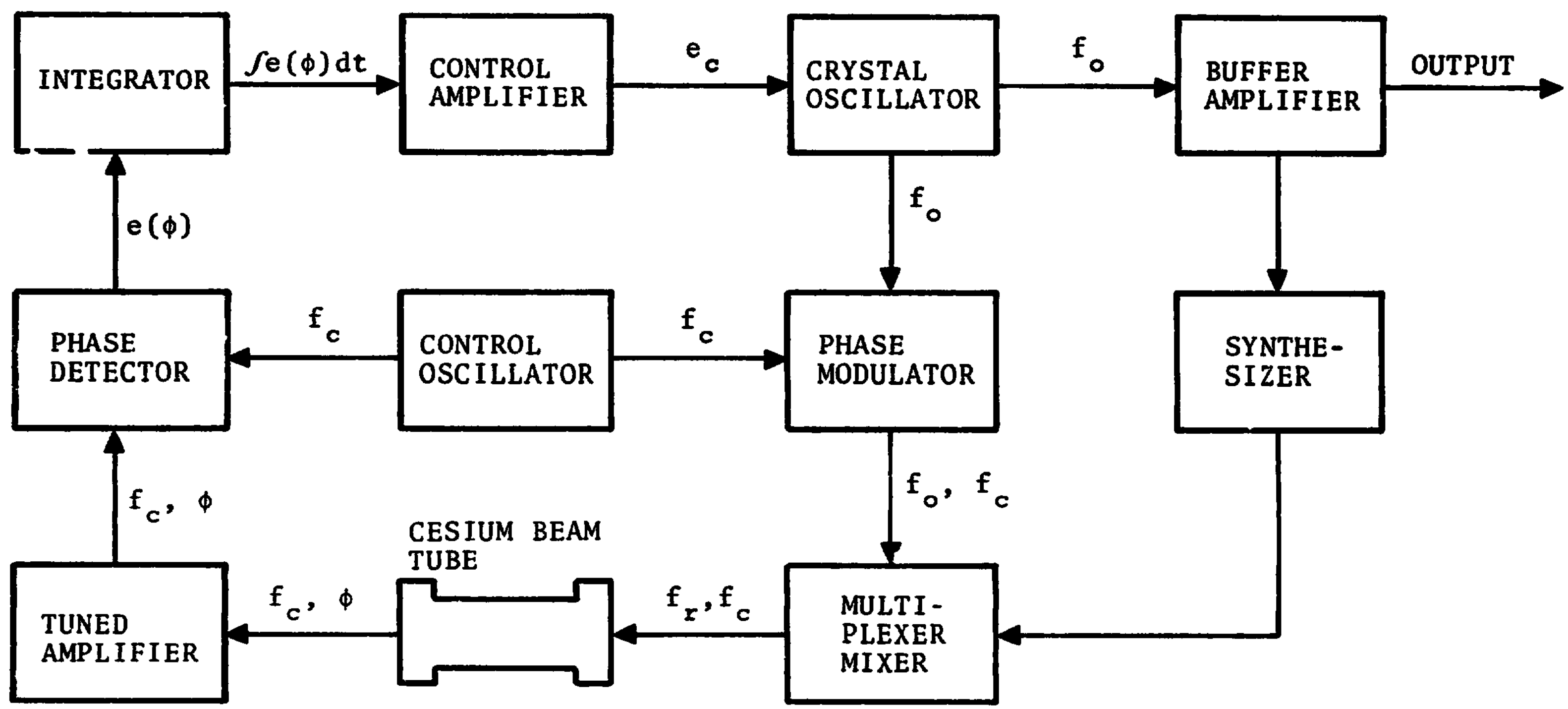


Figure B-2. — A typical cesium beam frequency standard.

signals produces an error signal, $e(\phi)$, at the output of the phase detector. An integrator is used to smooth the error signal and this smoothed signal, $\int e(\phi)dt$, corrects the crystal oscillator frequency.

The extremely stable operation of the cesium beam standard is due to the very high Q of the resonant response of the tube. A half-amplitude bandwidth of 550 Hz has been measured, indicating a Q of 18 million, at the center frequency of over 9000 megahertz.

Cesium beam time standards have been transported by airplane and automobile to points throughout the world. This endeavor has demonstrated the rugged and dependable qualities of a "flying clock" and the practicality this method of comparing widely separated time standards. The reliability of laboratory models of the cesium beam standard is given as better than a 15,000 hour MTBF. The cesium beam tube is specified to have a 30,000 hour MTBF.